DEVELOPMENT OF A MICRO-HYDROPOWER PRE-FEASIBILITY ASSESSMENT TOOL FOR DEVELOPING COUNTRIES

By

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I dedicate this work to Pepito,
whose purr always cheered me up.

Abstract

Isolated communities in developing countries struggle to meet their energy demands partly due to the difficulty in connecting to national electricity grids. Basic energy demands are often met with the use of expensive and polluting fossil fuels. An alternative way of meeting energy demands can be through the use of micro-hydropower (MHP) systems. For communities in mountain ranges with good hydrologic resources, community owned MHP can be a cost-effective technology that harvests the potential energy of rivers and generates electricity. The arrival of electricity to communities often brings numerous socio-economic benefits as well as improved livelihood.

Physical (e.g., head and flow) and economic requirements are essential for establishing the feasibility of MHP schemes, but social and environmental factors can also be critical for the performance and longevity of the scheme after its installation. There is a lack of available international studies on specific success and failure reasons. Community owned MHP feasibility evaluation requires an extensive holistic approach, and the success of schemes depends on the socio-economic characteristics of the community as well as other geophysical parameters of the environment. Schemes are operated and maintained by communities and their sustainability depends on the support and care of communities. The electrification of villages brings multiple livelihood improvements such as reduced drudgery, improved lighting, or overall comfort. However, there is a lack of international studies on livelihood improvements brought by the implementation of MHP schemes. Remote communities cannot carry out independent pre-feasibility assessments due to a lack of know-how. Local developers often identify potential sites by personal references and perform pre-feasibility assessments by sending a small group of engineers to record essential physical variables such as the head or the river flow. No holistic, efficient and easy to use MHP pre-feasibility assessment method exists.

The main objectives of this study were: (1) to create a framework to generate a scheme current success score (SCSS), identifying success and failure reasons; (2) to study the connection between livelihood improvements and scheme sustainability by evaluating a wide range of livelihood indicators from five broad livelihood categories: health, education, safety, community engagement and economy; (3) to create a MHP pre-feasibility assessment tool that can be used by communities and developers with the use of a multi-criteria decision method.

This study evaluated 35 communities from Nepal, Bolivia, Cambodia and the Philippines through site visits and interviews with developers, operators, key members of the communities and electricity beneficiaries. Failure and success reasons were recorded, and a framework to determine schemes current success score was created. The capability approach was used to measure the change in livelihood brought by the implementation of MHP schemes. The livelihood analysis was based on 17 communities from Bolivia and the Philippines, where 22 livelihood indicators were evaluated from five broad livelihood categories: health, education, safety, community engagement and economy. The analytic hierarchy process (AHP) was used as a multi-criteria decision making method to incorporate 15 key quantitative and qualitative criteria that affect the likelihood of success of community owned MHP schemes and create a pre-feasibility assessment tool. To validate the method, the pre-feasibility tool results were compared to the scheme current success score (SCSS).

Proper regular operation, ongoing strong support by the community, and the external long term support from the government or local developer were key factors for MHP scheme success. The most recurrent failure reasons were maintenance difficulties, extreme weather events, and the arrival of the national electricity grid.

Results from the livelihood analysis showed significant improvements in education, community engagement and economy. Improved lighting was identified as the most influential factor. Women appeared to benefit more from drudgery reduction and men from community engagement opportunities.

The analytic hierarchy process integrated the key qualitative and quantitative variables required for a MHP pre-feasibility study. Results were compared to the results of the SCSS analysis and showed a strong correlation of 0.868. The tool gave equal importance to the physical, social and economic factors, which were strongly more important than the environmental factor. Water availability, terrain quality, community cohesion and financial support were identified as the most important criteria affecting the likelihood of success of schemes.

This research identified the most common failure and success reasons and classified schemes across four countries by their success. The capability approach successfully identified the most common livelihood improvements that MHP schemes bring to communities and highlighted how communities value such improvements. A Micro-hydropower Pre-feasibility Assessment Tool (MHP-PAT) was designed that could be easily used and manipulated by developers and communities to generate assessments of the likelihood of success of schemes.

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Please detail the nature and extent (%) of contribution by the candidate:

The candidate developed the methodologies (80%), collected the field data (90%), analysed the data (100%), and led manuscripts' writing (thesis and first-authored papers) (80%). Overall the candidate's contribution was 90%. Co-authors were involved primarily in the editing of manuscripts.

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The undersigned certifies that:

- The above statement correctly reflects the nature and extent of the PhD candidate's contribution to this co-authored work
- In cases where the candidate was the lead author of the co-authored work he or she wrote the text

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Glossary of key terms

AHP	Analytic hierarchy process
ARW	Aggregated relative weights
DMS	Decision making scale
ELC	Electronic load controller
FDC	Flow duration curve
MHP	Micro-hydropower
MHP-PAT	Micro-hydropower pre-feasibility assessment tool
MCDM	Multi-criteria decision-making
NGO	Non-governmental organization
O&M	Operation and maintenance
PWC	Pair-wise comparison
RW	Relative weights
RoR	Run-of-the-river
SCSS	Scheme current success score

Research Outputs

Journal papers (under review)

1. Arnaiz, M., Cochrane, T. A., Calizaya, A., Shrestha, M. (2018). A framework for evaluating the current level of success of micro-hydropower schemes in remote communities of developing countries, *Energy for sustainable development.*.

2. Arnaiz, M., Cochrane, T. A., Hastie, R., Bellen, C. (2018). Micro-hydropower impact on communities' livelihood analysed with the capability approach. *Energy for sustainable Development.*

3. Arnaiz, M., Cochrane, T. A., Dudley Ward, N.F., Zhang, L. (2018). Micro-hydropower pre-feasibility assessment tool: facilitating universal energy access for developing countries, *Energy Research and Social science.*

1. Introduction and scope of research

1.1 General introduction and problem statement

Micro-hydropower (MHP) generation is the physical process of converting the potential energy contained in water into electric power or mechanical drive. MHP generation includes those systems with a power generation capacity in the range between 5 and 100kW, which commonly provides electricity to a local grid which is not part of a national grid. Remote communities in mountain ranges in developing countries often do not have access to the national grid. These communities frequently grow around rivers that often have enough flow and elevation difference to meet the energy demands of the village with the use of a MHP system. In the context of community owned MHP schemes, the energy generated is typically generated to meet some of the energy demands of a community such as electricity for lighting and small appliances, the electrification of small industries, or the mechanical drive of agricultural mills.

In developed countries, where electric loads are high and the national grid provides power to most communities, economies of scale foster large scale hydro-electric generation. MHP, however, is most relevant in remote communities in developing countries with no access to the electric grid, where communities can greatly benefit from MHP electricity generation (Pokharel et al., 2008). Isolated and less power demanding communities, which often meet their energy demands with more costly and polluting generators, can benefit from this locally generated energy source saving in fossil fuel costs, transportation charges and time, while avoiding grid dependence and preserving the environment (Wazed et al., 2008).

MHP can be a cost-effective energy generation solution for small isolated communities (Huang et al., 2014; Mainali et al., 2003), and it can bring numerous environmental and socio-economic benefits (Gurung et al., 2011; Pokharel et al., 2008). The implementation of MHP schemes brings comfort to communities and can generate livelihood improvements in health, safety and education, improve existing businesses, reduce drudgery or lower the cost of lighting (Baskoti, 2006). Increased education, added socializing opportunities and “improved general health conditions” have also been reported (Gurung et al., 2011). Amenity benefits are often more significant than community and household economic development (Murni et al., 2013).

The implementation of MHP schemes in developing countries is typically done by local NGOs. These, throughout the implementation stage, provide workshops on scheme operation and maintenance and help create a MHP village committee. NGO’s, which depend on government support or international aid, however, often do not have the resources to support communities after the implementation of schemes. Much like other humanitarian engineering projects, communities struggle to maintain schemes, and consequently these often do not operate for long. Abundant literature exists on the installation, operation and maintenance of schemes (Singh, 2009; Fulford et al., 2013; Mohibullah et al., 2004; Smith, 1994), however, there is limited available literature on scheme post implementation performance levels and community livelihood impact. A study over 16 schemes from Nepal, Peru, Sri Lanka and Zimbabwe and Mozambique showed signs of overall compromised sustainability (Khennas et al., 2000). Current scheme high failure rates indicate that there is a lack of understanding on scheme success and failure reasons, the communities' livelihood changes, and if a relationship exist between these two.

Community owned MHP technology is present in most developing countries. However, inefficient processes for MHP site identification have hampered the widespread use of the technology. Remote communities are often unaware of MHP technology and do not have the technical know-how to perform pre-feasibility assessments. Pre-feasibility assessments are done by local developers by sending a small team of engineers to measure physical attributes, such as the head or the water flow (Smith, 1994). However, site identification is a multidisciplinary task that requires the consideration of physical and economic quantitative data as well as social and environmental qualitative data, such as the communities' cohesion, or the alteration of the river biodiversity (i.e., by reducing the river flow when diverting water for the MHP scheme). Site assessments surveys have often only considered economic and technical factors and have overlooked social factors, which has led to posterior social conflict (Smith, 1994). Failing to address social issues has previously led to the loss of the communities' trust, resulting in the failure of schemes (Kabalan et al., 2014b). Social issues during the feasibility and operation stages of MHP schemes have to be addressed, as failing to do so can lead to losing the trust of the community. Thus, MHP pre-feasibility assessments require a holistic approach that considers a wide range of variables. However, some of the key variables that affect the likelihood of success of MHP schemes might change between countries. Thus, to identify the most important (and common to all countries) variables that affect the success of schemes, several countries should be considered.

Nepal is the leading country on community owned MHP, with 1152 schemes built since 1962 and 22830kW installed (Nepal Ministry of Finance 2015). Only 40% of the population has access to electricity and more than 80% of the population lives in rural areas (Gurung et al., 2011). However, pro-active governmental institutions, a strong private sector and fifty years of local expertise have resulted in significant socio economic advantages for MHP for remote communities (Mainali et al., 2013; Gurung et al., 2008). Several studies have reported on Nepal's opportunity to successfully provide energy to population in rural areas through MHP generation (Junejo, 1997; Pokharel et al., 2008).

Bolivia, one of the least developed countries of South America, has an electrification rate of 77.5% (www.hdr.undp.org). Under a hundred schemes have been built in Bolivia since the mid-1990s to help provide electricity to rural areas. However, a government bias towards a central grid and the lack of financial support and technical expertise hamper MHP development (Drinkwaard et al., 2010). Many parts of Bolivia have ideal geographic and social characteristics for MHP generation. A study of 9 MHP schemes showed significant enhancements in community livelihood, such as education, health and comfort (González et al., 2009).

The Philippines has numerous islands of volcanic origin with extensive hydrologic resources, which makes the expansion of the national grid highly costly, but provide ideal physical characteristics for the creation of local MHP schemes (i.e., steep mountains). Like in Bolivia, MHP has been developed since the mid-1990s by a few local NGOs implementing approximately a hundred schemes, and like in Bolivia, the country suffers from a lack of governmental support and no consistent subsidy system.

In Cambodia the overall national electrification rate is 29%, while in urban areas is a 100%, which exemplifies the difficulty in meeting the energy demands of rural isolated areas (www.smallhydroworld.org). MHP technology has not been developed and the few existing schemes are the result of individual entrepreneurial initiatives. No NGOs or governmental institutions exist fostering the implementation of schemes. There are, however, good underground hydrologic resources which have allowed for the installation of a few successful schemes from flowing springs.

The local developers in the four countries analysed did not evaluate the performance of schemes, nor did they analyse how these impacted communities' livelihood. None of the developers recorded data on success or failure reasons and they did not have a database with the current state of schemes. Only a few studies on single countries exist that outline descriptively the reasons behind the failure of schemes. No extensive international success and failure studies exists. Current literature on livelihood changes due to the implementation of MHP schemes is minimal. It is unknown if a connection exists between the scheme sustainability and the livelihood changes brought by the implementation of schemes. Communities are unable to perform pre-feasibility assessments and developers are often deterred from assessing potential communities due to high costs. For MHP technology to prosper in the context of developing countries, where there is a lack of available geodatabases and local expertise, efficient site identification is necessary.

Recording the most common success and failure reasons can help developers implement schemes more successfully. The development of a holistic framework to assess the current success level of schemes can allow developers to better understand the state of their schemes and create national and international databases. The evaluation of the livelihood changes that a MHP scheme can bring to a community can help developers implement schemes with consideration of post implementation livelihood benefits. Measuring livelihood changes can help developers understand if a connection exists between improved livelihood and scheme sustainability. To help guarantee the successful implementation and future performance of a MHP system, users should be involved in the evaluation of its prefeasibility. The creation of an easy to apply, non-technical, holistic pre-feasibility tool that considers the community's needs can allow remote communities and developers perform efficient preliminary assessments of the likelihood of success of schemes.

1.2 Research objectives

The main motivation of this research was to contribute to the current knowledge on community owned MHP schemes in developing countries and to help communities and developers generate pre-feasibility assessments. The main objectives of this research were to understand the most common scheme success and failure reasons, current scheme success levels and community livelihood impact and to create a pre-feasibility tool. This research had thus three interrelated objectives:

i. The first objective was to record the most recurrent reasons for success and failure of schemes and to identify and use the key variables for the success of schemes to create a framework to generate a scheme current success score.
ii. The second objective was to identify the most common livelihood improvements provided by the implementation of MHP schemes and to understand if a relationship exists between the livelihood improvements and the sustainability of schemes.
iii. The third objective was to create an easy to use MHP pre-feasibility assessment tool that can be used by communities and developers.

To address the research objectives, 38 communities with MHP schemes from Nepal, Bolivia, Cambodia and the Philippines were visited. However, only 35 schemes were considered suitable for this study. Developers, practitioners and electricity users were interviewed to reveal key information on the scheme-community relationship and to record scheme failures and current status. The theoretical framework capability approach was used to analyse the community livelihood changes brought by the implementation of schemes. The analytic hierarchy process was used to incorporate all the variables that affect the likelihood of success of schemes and generate a pre-feasibility assessment tool. To validate the tool, results were compared with the scheme current success score.

1.3 Thesis structure

The first two chapters of this thesis introduce the problem and the necessary background knowledge on community owned MHP schemes. Chapters three to five present individual but interrelated studies that progressively build the necessary knowledge and data to create the pre-feasibility tool. The following is the structure followed by this thesis:

Chapter 1: Introduction	Problem statement, need for research, scope of the thesis and the main objectives and thesis structure.
Chapter 2: Literature review	Background information on past and current MHP development, scheme elements and power generation, overview of the MHP scene in the four countries visited and preliminary information on pre-feasibility assessment key factors.
Chapter 3: Success and failure reasons and scheme current success score framework	Analysis of the most recurrent scheme failure and success reasons, recording of scheme failures in civil works and powerhouse, creation of a framework to determine scheme current success score and classification of the 35 schemes by success score.
Chapter 4: MHP impact on communities' livelihood analysed with the capability approach	Identification through the capability approach of the most common livelihood improvements classified by health, education, safety, community engagement and economy for Bolivia and the Philippines with a country and gender comparison. Study of correlation between community livelihood improvements and scheme sustainability.
Chapter 5: Micro-hydropower pre-feasibility assessment tool for developing countries.	The analytic hierarchy process is used as a multi criteria decision method to create a pre-feasibility assessment tool. The tool is applied to the 35 schemes and is validated by comparing its results with the scheme current success score results.
Chapter 6: Conclusions	Overview of the most important results and conclusions of each study. Recommendations for future research are presented as well.

2. Literature review

2.1 Past development and current status of large and small HP generation.

Hydroelectric energy has been the most successful renewable energy source throughout history, supplying close to 20% of the world's electricity consumption (Singh, 2009). Its efficiency, storage capacity and availability make it a unique energy source that has been widely exploited throughout the world.

Approximately 50% of the potential medium and large hydro schemes were exploited in Europe and North America during the first half of the 20th century (Paish, 2002). In Europe, small hydropower represents the main prospect for the future of hydropower generation, being its environmentally friendly character, especially for run of the river (RoR) systems, one of the main drivers for such tendency (Paish 2002).

Continents with less economic development, such as Africa, South America, and especially Asia, have barely exploited their large and small hydro potential (Figure 1). Asia, South America and Africa host many developing countries that lie between the Tropics of Cancer and Capricorn, where rainfall is greatest and hydraulic resources are paramount (Wadell et al., 1999).

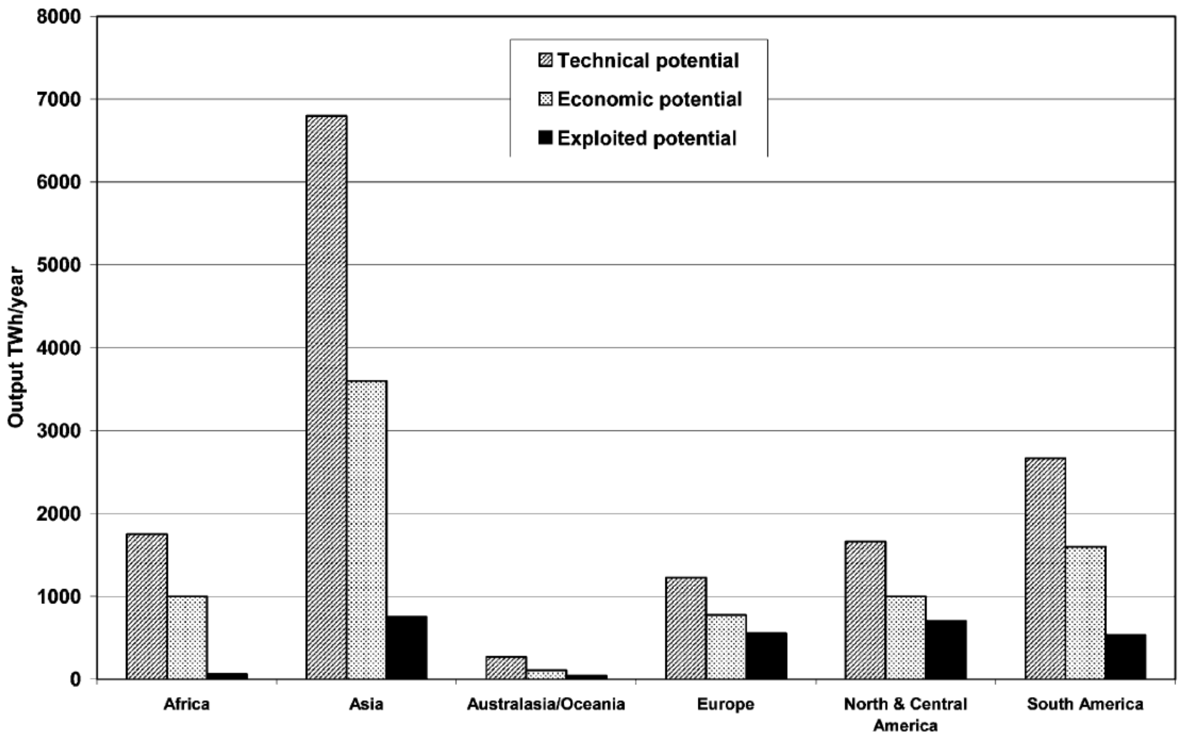


Figure 1. Exploited large and small hydropower potential by continent. Source: Paish, (2002).

The wider development and production of MHP systems began in Nepal in the mid-1970s with Swiss and German Aid programmes supporting the installation of Pelton and Crossflow turbines. The technology soon moved to Sri Lanka, Peru and Indonesia, among others. With the introduction of electronic load controllers (i.e., a system to distribute electrical energy according to demand) in early 1980s, MHP projects spread extensively around developing countries. The technology thrived in China, which was rich on unexploited hydrologic resources, and which now holds around 40% of all small hydro capacity on earth (Paish, 2002).

Governmental funding and policy changes encouraging sustainability and privatization of the electricity industry have fostered MHP generation around the world (Kirk, 1999). In developing countries, where hydrologic resources are better and power demand is lower, opportunities for MHP generation are higher. However, there is scarce information regarding the number of installed schemes, their power capacity, or their operational state.

2.2 MHP power generation and scheme elements

2.2.1 Power generation

The conversion of energy from a water source with a water mill is a technique that dates back to the third century B.C. With the invention of the first electric generator in late 19th century, hydro-electric generation thrived helping the industrial revolution. The advance in civil works and turbine technology led to bigger power plants, making hydroelectricity generation 65% of all renewable energy produced and a 16% of all global electricity consumption as of 2014 (www.iea.org).

Hydropower plant capacities can be classified by power brackets (Table 1).

Table 1. Hydropower generation classification.
Sources: CANRen, (2004); Mohibullah et al., (2004); Wazed et al., (2008).

Size	**Power**	
	Low end	High end
Pico	-	5 kW
Micro	5 kW	100 kW
Mini	100 kW	1 MW
Small	1 MW	10 MW
Medium	10 MW	100 MW
Large	100 MW	-

Medium and large hydropower schemes have dams and reservoirs that allows them to deliver the greatest power among the range of hydropower schemes. These typically work with reservoirs to achieve desired water head values to release water to adapt to electricity prices. Such schemes require higher capital cost and have a significant number of undesired ecologic and social consequences

(Kumar et al., 2014). These hydropower schemes greatly affect landscape characteristics, act as sediment traps and ecologic barriers and greatly affect the overall river biodiversity. However, reservoirs can also function as flood prevention systems and allows for regulation of yearly river flow (alleviating drought periods).

Run of River (RoR) schemes are the most common schemes for MHP generation. These have very little or no storage capacity and their design is based on the minimum year-round water flow. Although MHP schemes have minimal impact on the environment, these often lack water in dry season and cannot meet peak demand periods. RoR schemes are cheaper (i.e., no dam required) and can be designed and built with a small team of engineers and the help of a community. These characteristics have made RoR schemes more suitable for community owned MHP (Kumar et al., 2014).

MHP generation can adapt to different power demands through the use of batteries, ballast load control with resistors, storage tanks or weirs. However, the use of resistors (submerged in water or exposed to air) are the most common systems used to control demand due to their low cost and ease of installation. The water diverted for electricity generation can further be used for multi-purpose water demand systems (i.e., systems combined with agriculture irrigation or potable water storage), which, by higher levels of stakeholder involvement, increases MHP scheme sustainability.

Remote communities sometimes operate small man-powered machinery such as grain or timber mills. MHP can drive machinery mechanically, by use of belts and shafts, thus reducing village drudgery. Mechanically driven systems have been successfully used in developing countries, partially due to the lower efficiency losses (approximately 10%), compared to the electrically driven systems (approximately 50%) (Paish, 2002). Both systems often function in parallel.

2.2.2 Scheme structure

In a typical MHP scheme, water for generation can be obtained from nearby streams by diverting a portion of the water to create a RoR system (Harvey et al., 1993). This can be installed directly on the river, or diverted by means of a canal.

In a typical RoR scheme multiple elements exist from the water intake to the community (Figure 2).

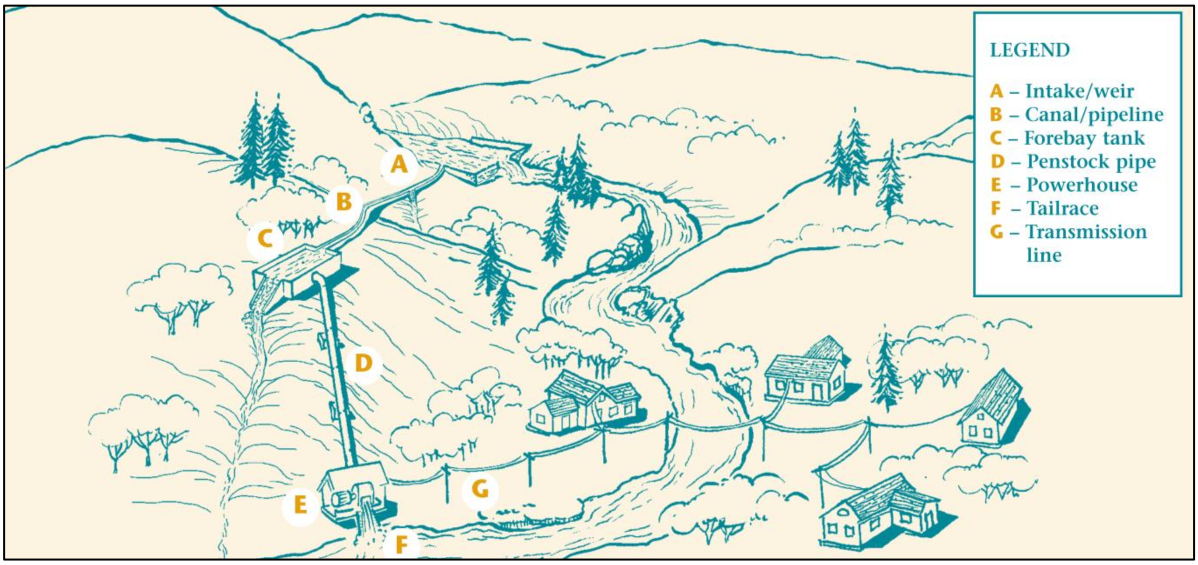


Figure 2. Run-of-the-river scheme. Source: CANRen, (2004).

A- **Intake/weir:** structure on the river to allow for the diversion of part of the water flow. It typically includes a system of bars or arrays to prevent fish and other debris from entering into the penstock and damaging the turbine. For maintenance purposes, a gate can habilitate complete closure of the system.

B- **Canal:** canals or aqueducts that carry water to an area at a very similar elevation level, avoiding potential energy loss, where the forebay tank is situated. A gravel trap is sometimes situated through the canal, which, by means of the coanda effect, separates coarse particles from the water to prevent turbine damage. By approaching the powerhouse without losing elevation, the length of the penstock is reduced, which is especially important as often this is the most expensive element of the scheme, which, in case of high head, can be up to 30-40% of the capital cost (CANRen, 2004; Gatte et al., 2004; Singh, 2009).

C- **Forebay tank:** a tank which acts as the last system to eliminate water debris by means of the coanda effect and a trash rack. Like the de-silting tank, it functions as a sand trap. It guarantees a connection to the penstock free of air, thus preventing penstock and turbine damage.

D- **Penstock pipe:** connection from the forebay tank to the turbine, delivering high pressure water.

E- **Powerhouse:** where the turbine, generator and load control system are situated. It contains the elements in charge of converting the mechanical energy of the rotating turbine into electricity.

F- **Tail race:** a channel that directs the water coming out of the turbine back to the river. Often the tailrace water is used for other water demanding activities, such as irrigation or grain mills.

G- **Transmission line:** the wiring necessary to transmit the electricity generated in the powerhouse to the households. If the powerhouse is far from the community centre (above 1 km), transformers might be used to reduce electricity loss.

2.2.3 Electricity generation

The powerhouse contains the scheme elements in charge of converting the potential energy of the water into electric energy ready for use.

The power that can be extracted from the high pressure water depends on the head (h) (i.e., vertical distance between forebay and turbine), the volume of water (Q), and the efficiency of the system (η) (Eqn. 1),

$$P_{net} = g\ Q\ h\ \eta \quad [\mathrm{kW}] \tag{1}$$

where P_{net} is the power after efficiency losses [kW], g is the acceleration of gravity [m/s^2], Q is the volume flow [m^3/s], h is the head [m] and η is the total efficiency. Note that here water is considered to have a density of 1000 kg/m^3.

Only a certain amount of energy will effectively be extracted from the water, as friction, mechanic and electric losses will affect the overall scheme efficiency (Figure 3).

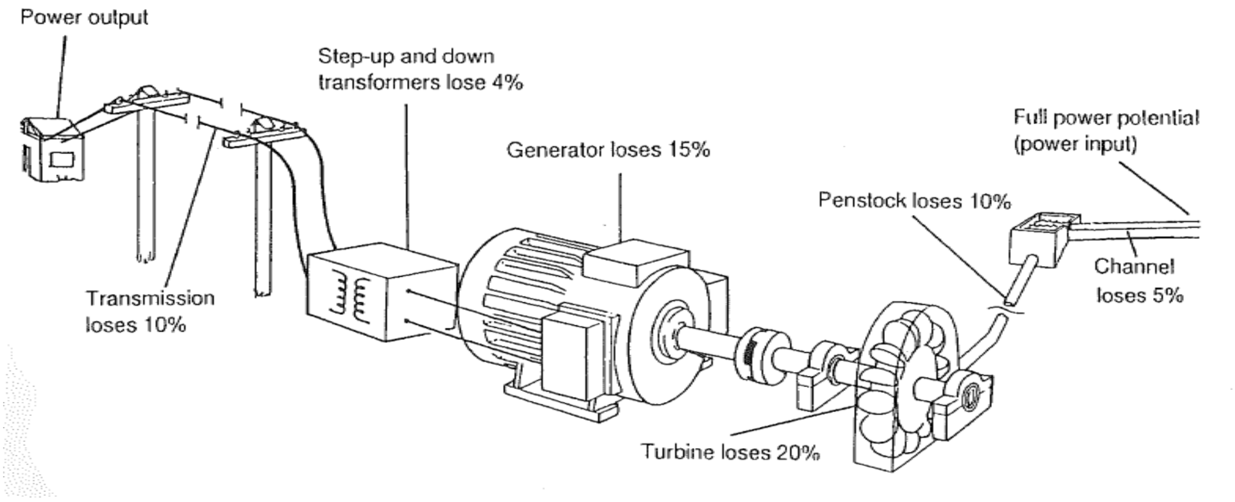


Figure 3. Common MHP system efficiencies. Source: Harvey et al., (1993).

The total efficiency of the system is obtained by multiplying the efficiencies of all the elements of the system (Eqn. 2).

$$\eta_{total} = \eta_{\,civil\ works}\,(0.95)\ x\ \eta_{\,penstock}\,(0.9)\ x\ \eta_{\,turbine}\,(0.8)\ x\ \eta_{\,generator}\,(0.85)\ x\ \eta_{\,transformer}\,(0.95)\ x\ \eta_{\,line}\,(0.9) = 0.5 \tag{2}$$

Thus, a MHP scheme with 50 m head and 0.2 m^3/s would produce 50kW, an average value for a MHP scheme that can power 100 to 300 households.

The use of new materials, better construction practices and more efficient machinery have increased the overall efficiency of this type of schemes sometimes achieving figures up to 60-70% when generating electricity (CANRen, 2004) and figures up to 90% when transmitting direct mechanical drive (Wazed, 2008). In the context of community owned schemes in developing countries, where operation and maintenance often is inadequate, the typical range of efficiencies found in the studied schemes was 40-60%. However, diesel generators, the most direct counterpart to MHP, have performances in the range of 20-60% and generate undesired emissions such as CO_2, making hydropower generation a more environmentally friendly and efficient energy source.

In the context of renewable energies in developed countries, the high efficiency of hydropower generation has been one of the main rationales behind the use of the technology (Figure 4).

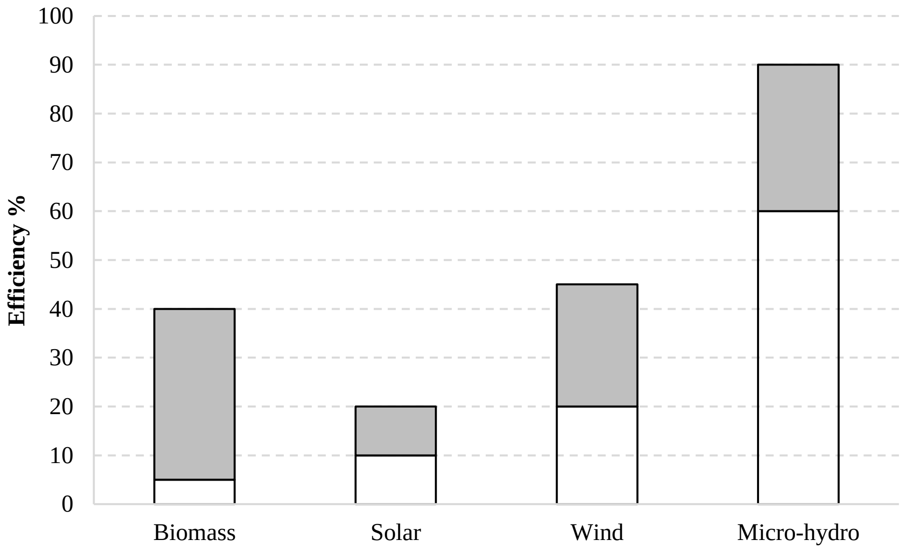


Figure 4. Common range of efficiencies for the most common renewable energy sources.

2.3 Examples of MHP in developing countries

In this section the MHP characteristics of the four countries visited (Nepal, Bolivia, Cambodia, and the Philippines) are briefly explained and imagery of representative scheme parts of each country is shown.

2.3.1 MHP in Nepal

Country overview

Due to its rugged mountains, Nepal has struggled to create an extensive and reliable national electricity grid. The central government, however, has recognized that the electrification of communities is a key factor for human and economic development. Since 1962, 1152 MHP schemes have been officially installed (Nepal Ministry of Finance, 2015), however, the unofficial number of schemes functioning (including those with only mechanical drive) is suspected to be between 2,500 and 3,000. MHP has rapidly grown in number of schemes, engineering expertise, construction methods, and operation and maintenance principles. Such growth has been possible thanks to a strong subsidy system by which the central government often provides 50% of the capital cost of schemes, and local districts use taxes to provide up to a 30%. The remaining 20% is provided by the community through involvement with the construction of civil works and cash collection.

A complex network of associations, private companies and governmental organizations, as well as trained engineers, developed MHP in the country. With the appearance of electronic load controllers in the 1980's, many European countries not only brought the engineering and economic means to construct efficient and modern schemes, but also planted the seed for the study and research of small hydro-power. The Turbine Testing Lab (Kathmandu University), built by the Norwegian organization NORAD, is one of the six laboratories in the world completely dedicated to the research of more efficient and durable turbines and, by studying turbine erosion, aims to better adapt to the high concentration of silt in Nepalese rivers.

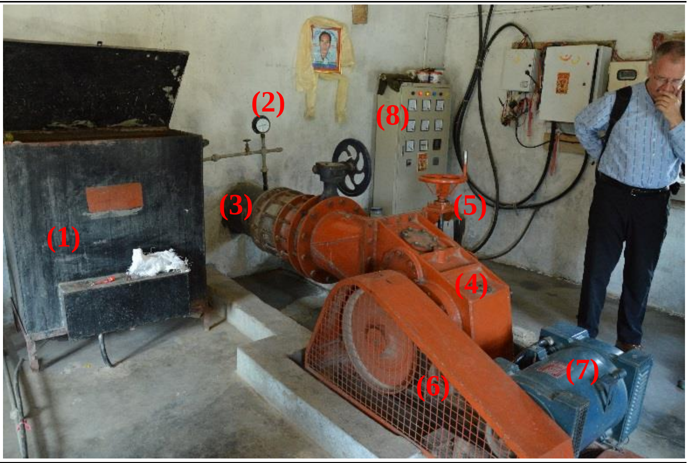
Nepal is considered the world reference in community owned MHP. In Nepal, the construction techniques used in the schemes visited showed the highest degree of engineering design expertise, construction methods and operation and maintenance practices. An example of this are the de-silting bays on headrace canals (picture 4, Table 2), a scheme element not installed in the schemes visited in Bolivia, Cambodia, or the Philippines. MHP village committees were adequately organized, schemes were operated diligently, and overall maintenance was good. Hydrologic resources were better utilized, and often schemes not only provided electricity to household, but powered small industries (also known as end-uses) (picture 3, Table 2). Several studies exist on the effects on the communities' livelihood brought by the implementation of schemes (Pokharel et al., 2008; Gurung et al., 2011).

Representative scheme elements

Table 2. Scheme parts in Nepal.

View of penstock made of steel sections supported by rock and concrete pillars, from forebay tank (not visible) to powerhouse. Powerhouses in Nepal often have an upper floor for the operator to live in.

Interior of a powerhouse showing the electromechanical group: open water tank with resistors (1) with pressure gauge (2), penstock (3), Crossflow turbine (4), turbine vane adjuster (5), rectifying belt (to adapt to rpm generator needs) (6), generator (7) and electronic load control (8).



Mechanically driven end-uses. At the right, the long shaft is connected to a localy made turbine (not shown). A belt (lower right) is connected to a corn mill (not shown). A loose belt (centre) is connected to another shaft that drives two rice processing machines.

A de-silting bay on the main aqueduct. Silt deposits at the bottom of it. A plug (metallic cylinder with a wooden stick) is lifted periodically to fully empty the tank from underneath, dragging all silt and debris out of the tank.

2.3.2 MHP in Bolivia

Country overview

In Bolivia, MHP technology has experienced a steady growth since the early 1990s. Construction techniques and community management methods are based upon the theory developed in Nepal. Developers have applied modern building techniques, which has led to the successful implementation of multiple schemes. However, despite the presence of a few NGOs that have successfully installed schemes, the central government has not recognized MHP and no subsidy system exists. No private sector exists producing parts for the electromechanical group, and often these need to be acquired from neighbouring countries. Developers, who depend on international financial aid, are thus economically constrained and forced to build MHP under strict budget limitations.

The area located between the 'altiplano' and the lowlands of the Amazon is the most convenient for MHP generation due to the high hydrologic resources and steep mountain ranges. However, the sub-tropical climate conditions of such area have greatly challenged engineers and communities. Schemes suffer failures on the civil works frequently due to landslides during strong weather events (often affected by the El Niño), which also creates flush floods that can destroy the intake structure (picture 3, Table 3). When communities do not have the economic or technical means to repair critical failures, schemes are left abandoned.

Furthermore, the dense jungle vegetation greatly hampers operation and maintenance duties. Schemes often extend hundreds of meters through steep valleys, which forces operators to fight vegetation growth under difficult and dangerous conditions (picture 2, Table 3). This results in inefficient maintenance, and debris often damage turbines and clog pipes which lead to mechanical failures (picture 4, Table 3).

The electromechanical group is very similar to the systems used in Nepal, only the ballast control is significantly different. Bolivian developers use a system of enclosed resistors with recirculated water (picture 1, Table 3). The resistors are smaller (and cheaper) and can be easily replaced. However, these fail often, which leads to higher intensity circulating through the remaining resistors, thus increasing the possibility of a chain reaction failure.

The MHP village committee is formed following similar principles as those used in Nepal. However, developers often allow communities to decide on the operation and maintenance duties, which are often done by several members of the community simultaneously, whereas in Nepal two or three operators are pre-selected, trained, and paid a full time salaries to maintain the scheme.

The community livelihood changes brought by schemes are not quantified by local developers, only one study exist on specific livelihood indicators (González et al., 2009).

Representative scheme elements

Table 3. Scheme parts in Bolivia.

Interior of a powerhouse showing the electromechanical group: polyethylene penstock (1) pressure gauge (2), Crossflow turbine (3), turbine vane adjuster (4), rectifying belt (5), generator (6), enclosed ballast load control (7), electronic load control (8).	
Overgrown jungle vegetation and deposited debris on civil works (canal and forebay tank) on a non-operational scheme due to a landslide.	
Improvised intake structure. When water is diverted from a big river prone to flash-floods, it can be better to have an intake structure that can easily be re-built.	
Pelton wheel with erosion marks on the buckets as a results of inadequate water de-siltation.	

2.3.3 MHP in Cambodia

Country overview

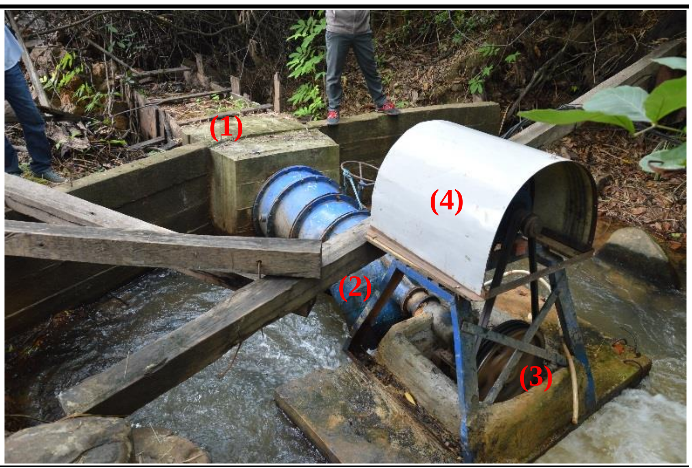
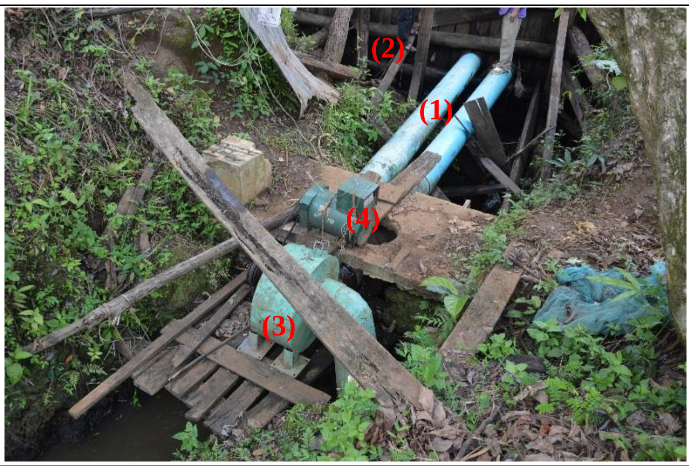
Due to the lack of national databases, it is difficult to know how many MHP schemes exist in Cambodia. No organization, NGO or otherwise, is actively installing schemes and no governmental initiative exists to use MHP as a way to provide rural electrification. However, good underground water resources have allowed for the successful implementation of several schemes around the country. Individual entrepreneurs have utilized simple electro-mechanical principles, rudimentary axial turbines and off the shelf generators to harvest the potential energy of water. However, no studies on the effect of the livelihood changes brought by the implementation of schemes exist.

Several low mountain ranges exist in the country, however, the existing schemes are all low head schemes (i.e., 3 to 10 meters) that use axial turbines with big separated vanes (picture 2, Table 4) driven by very high flows (100 to 500 l/s). Due to the low velocity of the water, turbines and penstocks suffer very small degradation, de-silting is not necessary, and overall operation and maintenance is much simpler. Penstocks often connect to water ponds, and a rack in such connection acts as the only debris filtering measure (picture 3, Table 4). Without the need to eliminate debris and silt, the civil works are much simplified and no intake structure, de-silting bay, canal or forebay tank are necessary, thus highly reducing scheme costs. The lack of ELCs, however, forces operators to carefully open the main penstock valve according to the communities' power needs (adjusting the speed of the turbine to maintain 220V).

No MHP village committees exist and the operation and maintenance is handled informally by community members.

Representative scheme elements

Table 4. Scheme parts in Cambodia.

Scheme parts of the generation group with a concrete and steel (blue) penstock (1), axel turbine (inside penstock) (2), rectifying belt (3) and generator (4).	
A typical axial turbine with vanes at the bottom (from where the inflow comes) and axel at the top.	
Pond fed with all year round underground water with intake gate at right.	
Scheme parts of the generation group with two polyethylene pipes as penstocks (1), wooden weir (2), axel turbine (3) and generator (4).	

2.3.4 MHP in the Philippines

Country overview

MHP implementation in the Philippines started during the early 1990s. Rural electrification through MHP schemes has become increasingly popular, and nowadays over a hundred schemes exist (as stated by local developers). The Philippines is a country comprised of more than 2000 inhabited islands, many of which do not have access to a national electricity grid and require local energy generation methods. Steep mountain ranges of volcanic origin and good hydrologic resources provide the basic physical criteria necessary for MHP generation. These factors make the Philippines an ideal country for MHP generation. However, like in Bolivia, the government does not recognize MHP and no local private companies exist producing MHP scheme parts. Thus, developers are forced to build with limited resources and strict budget limitations.

The design, construction and operation and maintenance principles are inherited from Nepal. Like in Bolivia, strong weather events coupled with deficient maintenance are the main reasons behind scheme failures. Most failures happen in typhoon season, when strong rains create landslides, excess debris and flash-floods (picture 2, Table 5).

Like in Bolivia, scheme parts are very similar to those in Nepal, and only the ballast control is different. In the Philippines, the resistors are typically placed encaged in air (to prevent fires). These are larger and more expensive, but fail less (i.e., they are not in contact with water and are more capable of withstanding high intensities) (picture 3, Table 5).

MHP village committees operate similarly to those in Bolivia, and communities are also more flexible on the scheme operation and maintenance procedures.

No studies currently exist on changes brought by the implementation of schemes on specific livelihood indicators. Like in Nepal and in Bolivia, developers leave communities after the implementation of schemes and do not perform an evaluation of the livelihood impacts.

Representative scheme elements

Table 5. Scheme parts in the Philippines.

Interior of powerhouse with polyethylene penstock (1), Crossflow turbine (2), generator (3) and electric protections (4). Due to the lack of ELC, the voltage is regulated by the turbine vane valve (5).	
Forebay tank with poor construction principles (i.e., curved) and very poor maintenance status.	
Encaged resistors that dissipate energy.	
Rudimentary repair techniques for cracked penstock.	

2.4 MHP pre-feasibility assessment

2.4.1 Pre-feasibility assessment available tools

Evaluating the feasibility of a micro-hydropower scheme involves multiple factors from different interrelated factors such as the physical, social, environmental and economic.

Due to the high number of affecting variables, experience and subjective judgement is required to evaluate the likelihood of success of a potential scheme. In Nepal, the combination of local knowledge acquired through history and expertise by local engineers have allowed for the evaluation of correct site identification. Nowadays government institutions are in charge of site evaluation. A team of experts gather relevant information about the site, and generates a preliminary report. The conclusions of such report are then shared with the community, which decides if it is convenient to contract private engineering services for an advanced feasibility study.

Several mathematic tools, software packages, excel spreadsheets, and online applications have helped engineers, companies, local entrepreneurs and academics to study, develop, and construct MHP schemes around the world. Some of the most common programs for MHP calculations around the world are HOMER software (HOMER Energy, 2017), used by more than 150,000 users, or RETScreen (Natural Resources Canada, 2015) with more than 400,000 users. Users range from individual engineers, academics or small organizations to private companies. These programs only consider quantifiable physical factors (i.e. flow rate, CO2 emissions, losses or efficiencies), and quantifiable economic factors, such as capital cost, facility lifetime, return rate, etc. Some organizations offer online-calculators and excel applications such as www.powerspout.com, www.rockyhydro.com or www.nooutage.com, which consider some of the most significant variables needed to calculate the potential power output of a potential MHP scheme.

HOMER can also be used to implement multiple power systems into a micro-grid. It allows for the individual evaluation of the economic and technical feasibilities of a number of technologies for energy generation, including MHP, photovoltaic, wind, and biogas. By introducing potential energy inputs, it generates a cost analysis, an electric load supply-demand assessment as well as an evaluation of the environmental effects, among others.

Online systems, spreadsheets, and specific software, require the introduction of multiple variables, or inputs, to generate results, or outputs. A list of the most common inputs and outputs is shown (Table 6).

Table 6. Common inputs and outputs for the most common pre-feasibility assessment tools.

Inputs	Outputs
- Water flow characteristics (FDC) - Head, penstock length - Power demand - Number, size and characteristics of turbines - Electric components of the electricity generating unit	- Annual energy production and energy revenue - Capital cost and O&M costs - Amortization rates and payback periods - Carbon emissions reduction

Such tools only consider quantifiable data and do not consider the broad spectrum of factors that affect the feasibility of a MHP scheme. The complexity of the interface demands a high level of education, leaving such tools impractical for remote communities in developing countries. This situation prevents small communities from getting the necessary expertise to evaluate the feasibility of a MHP scheme (Nigim et al., 2004).

In Nepal, the local knowledge and experience of experts is more regarded than the use of speciality software. The experience of developers and their capacity to balance installation costs and scheme performance while addressing social issues was found fundamental for the success of schemes (Kabalan et al., 2014). The difficulty in analysing and incorporating qualitative factors in pre-feasibility reports has often forced engineers to neglect or overview such factors (Smith, 1994). Schemes have often been implemented without analysing key qualitative data, such as the assessment of the communities' social attributes. A study conducted in Malaysia of six communities concluded that to be able to create realistic MHP installation guidelines to satisfy the needs of rural communities, more research is required into understanding the success factors of MHP (Murni, 2013).

In the context of most developing countries, scheme feasibility studies are often done without the support of any mathematical objective tool. To avoid human biased decision making and to include all qualitative and quantitative criteria that affect the likelihood of success of schemes a multi-criteria decision method (MCDM) can be used.

2.4.2 Multi-criteria decision-methods

Multi-criteria decision-methods are logic techniques to compare and rank potential outcomes of a combined set of criteria, generating a best solution to a complex problem. Decision making methods have been widely studied and used since the 20th century. Traditional decision making methods converted all criteria into a single unit, to allow for mathematical operations. Many decision problems, however, required the consideration of different type of criteria.

Some of the most popular methods for MCDM, with their advantages and disadvantages with consideration to the goal of our study, are described (Table 7)

Table 7. Advantages and disadvantages of MCDMs for a MHP pre-feasibility assessment.

MCDM	Advantages	Disadvantages
Elimination and Choice Expressing Reality (ELECTRE)	- Allows for structural view of the decision problem. - Widely used and mathematically solid. - Can include both qualitative and quantitative data. - Through the objective analysis of the attributes of the alternatives, the overall subjectivity of the process is reduced.	- Finite decision alternatives. - Complexity of operations do not allow for easy external input. - The structure of the system does not fit the necessity of our problem.
Simple Multi-Attribute Rating Technique (SMART)	- Simplicity and objectivity of calculation process. - No subjectivity over the ranking of alternatives. - A value function can generate a mathematically sound result. - New alternatives can be added to the model, common internal scale of criteria.	- A common internal scale of measurement needs to be chosen, which is not possible with the broad nature of the criteria of our study, sometimes qualitative, sometimes quantitative. - Too simplistic, not allowing for a high number of alternatives. - Does not allow for qualitative criteria.
Preference Ranking Organization Method or Enrichment Evaluation (PROMETHEE)	- Simplicity of calculations. - Allows for fast modification of thresholds of criteria. - Comparative numeric value over the different alternatives.	- Full subjectivity over qualitative criteria ranking. - Complexity of operations do not allow for easy external input. - Requires pre-existing decision alternatives. Not applicable for our model.
Analytic Hierarchy Process (AHP)	- Simple hierarchical structure of complex problem. - Easy to understand mathematics and final results, allowing for external input and modification. - Ideal number of alternatives and criteria equivalent to the alternatives and criteria of the intended. - Used in similar engineering problems.	- Subjectivity in pair-wise comparison. - It does not allow for dependence of the variables. - The quality of the result will depend on the quality of the structure and pair-wise comparison.
Analytic Network Process (ANP)	- Allows for the creation of a structure over a very complex multidisciplinary problem. - More generic, forcing for specific definition of interaction of all variables, allowing for better understand of all interdependencies. - Allows for dependency between variables.	- Factors need to interrelate, to feedback each other through levels. - Explanation of mathematical model is difficult. - Specific non flexible software is required. - Verification and understanding of results is complicated. - High levels of subjectivity in criteria pair-wise comparison.
TOPSIS	- Simple and fast mathematically sound calculations. - Easier to use than most other methods. - Possible to easily add new criteria.	- Requires an ideal bets scenario for comparison. - Criteria should be independent. - Does not allow for a hierarchical model.

Other MCDMs have been considered, including Stated Preference, Revealed Preference, Data Envelopment Analysis (DEA), Evidential Reasoning Approach (ERA), Weighted Sum Model (WSM), or Bayesian network. The reasons behind discarding them are inappropriateness of the dimensions of the method (i.e. number of criteria and alternatives) and unsuitability of overall objective with our objective (i.e., obtaining a numeric result to qualify the likelihood of success of a potential scheme).

AHP and ANP are the two systems identified with no apparent limiting condition, all others have at least one disadvantage that classifies the method as unviable. AHP stands out for its simplicity, capacity to be manipulated and for allowing for easy incorporation of external input and pair-wise comparison changes. ANP stands out for allowing for deeper understanding of the interaction between different criteria and for allowing for dependence. However, the ANP requires the definition of the bidirectional relationships through the levels of criteria, and, for our study, the relationship between criteria are unidirectional.

The selected MCDM for the intended tool is thus the AHP. The main disadvantages of the AHP can be mitigated, that is, dependence of criteria can be reduced by appropriate definition of criteria, and subjectivity of pair-wise comparison can controlled by the consistency ratio (Javanbarg et al., 2012).

Analytic Hierarchy Process

The analytic hierarchy process is a numerical method for the analysis of complex decisions. Developed by Thomas L. Saaty (Saaty, 1977), it has been widely used around the world by businesses, organizations, governments, industry, and it is taught in universities around the world as a MCDM.

The method allows for the incorporation, in a mathematical model, of qualitative subjective information and quantitative objective information. In any problem, some of its affecting variables can be represented in numerical scales, and such values need to be interpreted according to how adequate they are towards meeting a goal. However, in many complex problems, there is a number variables that we don't know how to measure, or quantify, and that can only be assessed with subjective qualitative criteria. Complex problems that require decision making, such as pre-feasibility studies, often involve both types of information.

AHP allows for the integration of a high number of variables compared to other MCDM tools. However, it requires a number of subjective pair-wise comparison evaluations to measure the relative importance of such variables. Such subjective evaluation is a common problem in MCDM, as qualitative criteria needs to be weighted somehow against other criteria. The AHP, in contrast to other methods, has a way to evaluate the quality of the subjective pair-wise comparison by using a consistency ratio.

To create an AHP model a four step method is used:

1st. Hierarchical division: Construction of a model that consists of multiple levels of decision attributes (Figure 1).

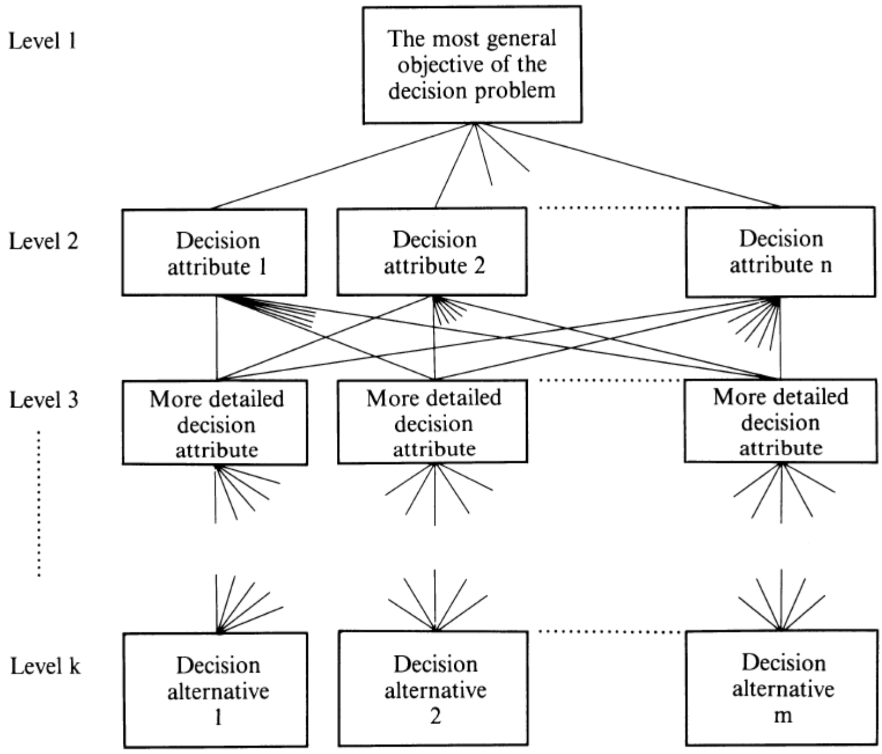


Figure 5. Standard form of decision model in AHP. Source: Zahedi, (1986)

The top level of the model represents the decision maker's goal. The intermediate levels represent those attributes that describe qualities of what is being evaluated. The last level of the model represents the alternatives (i.e., the different scenarios/options to be compared) to be introduced in the model.

2nd. Pair-wise comparison (PWC): the decision attributes must then be compared against each other to evaluate their relative importance towards the decision maker's goal. Psychology studies suggest that "it is easier and more accurate to express one's opinion on only two alternatives than simultaneously on all the alternatives" (Ishizaka et al., 2011) . Thus, all decision attributes from each level are subjectively pair-wise compared, establishing a relative weight value. The weighting describes "how many times more dominant is one element than the other with respect to a certain criterion or attribute" (Saaty, 1990). The method can integrate multiple decision maker's criteria by averaging the PWCs, thus generating a consolidated result. Several judgement scales can be used to numerically compare the decision attributes. A 9 point linear scale can be used as a system to give pair-wise value to the different comparisons (Saaty, 1990). A study found that the use of different scale systems, such as root square or logarithmic, can provide more accurate results depending on the nature of the consistency ratios and final goals desired (Franek et al., 2014). The same study concluded that Saaty's 1-9 linear scale, which is based on psychological observations, is, overall, the most favourable option.

A consistency ratio is then used to measure the consistency between the answers given by the decision maker, allowing for a maximum threshold of inconsistency. Such threshold guarantees the quality of the rationale used when attributing weights throughout the pair-wise comparison process (Franek et al., 2014).

3rd. Relative weights: a matrix (Eqn. 1) is constructed for each decision attribute for each level. These matrices (also known as reciprocal matrices) contain the PWCs and the reciprocal counterparts:

$$A = \begin{bmatrix} w_{11} & w_{12} \cdots & w_{1n} \\ w_{21} & w_{22} \cdots & w_{2n} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nn} \end{bmatrix}, \qquad [1]$$

where,

A= decision matrix
w_{12} = How many times decision attribute 1 is more important than decision attribute 2
$w_{21} = 1/\ w_{12}$
$w_{11}, w_{22} \ldots . w_{nn} = 1$

Determining matrix *A* requires numerous PWCs, and the evaluator can (and will) be inconsistent when answering. In order to ensure the effectivity and mathematical validity of the method, the weighting of the attributes must be consistent (i.e., if black is 2 times more important than white, and black is 3 times more important than red, then white must be 1.5 times more important than red). A ratio developed by Saaty called Consistency Ratio (CR) sets a maximum threshold of a 10% in the inconsistency of the weighting of the variables (Saaty, 1990). Such threshold ensures that the weighting is precise enough so that the system is consistent.

The reciprocal matrix allows for the calculation of the relative weight of each decision attribute thought the maximum eigenvector *x*, which contains the relative weight each decision attribute (Eqn. 2).

$$Ax = \lambda_{max}\, x \qquad [2]$$

The eigenvector represents "a numerical ranking of the alternatives that indicates an order of preference among them" (Saaty, 2003).

4th. Aggregated relative weights: the final step calculates the total influence (total aggregated weight) over the decision maker's goal (level 1) of the alternatives of the last level (k). The relative weights (eigenvectors) of each level must be aggregated by simple multiplication through the k levels of criteria, that is, the hierarchical multiplication of the eigenvectors.

2.4.3 Pre-feasibility factors

The criteria affecting the likelihood of success of MHP schemes can be grouped in four broad factors: physical, social, environmental and economic.

i. Physical factor

Power potential: the difference of altitude between the powerhouse and the water source, the head, must meet the power extraction desired (Paish, 2002). The water source, typically a river or stream, must provide sufficient water to meet the projected power output, and must do it all year round. Schemes are usually dimensioned for the flow of the river during dry season. If the estimation of the dry season flow is not correct, the scheme will not be able to meet the communities' energy demand. Data from at least one year (10 desired) of the water source is essential for an adequate feasibility study. A flow duration curve (FDC) is a necessary figure to understand the water flow throughout the year, and provides fundamental information for turbine choice (Harvey et al., 1993).

Construction, operation and maintenance: MHP is a site-specific technology and its feasibility depends partially on the relative position of the community to the water intake. On one hand, it might be necessary to seek water intakes that have better head and flow values but are far away, thus making the scheme construction more costly, increasing the probability of scheme failures and making more difficult its maintenance. On the other hand, closer intakes might have worse head and flow values, but are cheaper and easier to maintain. Intake distance is thus a key variable on scheme feasibility. The geological characteristics of the terrain affect the ease of access to the area, and the terrain stability determines the probability of landslides that can damage, or completely destroy, the MHP scheme. Transportation possibilities and ease of access to the site of study must be such that the civil works can be constructed, and the facilities maintained (Harvey et al., 1993).

ii. Social factors

Community's cohesion and organization: throughout the implementation process of a MHP schemes, a village committee is created for the administration and the operation and maintenance of the scheme. Unity in the community, past experiences on communal projects, and administrative skills are necessary community characteristics for the scheme to function adequately. The organizational capacity and financing methods of the community will determine the likelihood of acquiring the necessary funds for the maintenance of the power plant. Community based management contributes substantially to solving technical problems, management decisions, and help handle socio-economic issues that arise promptly. The lack of such management skills can lead to operational delays, high costs in O&M, technical problems, critical failures, and the ultimate decay of schemes (Singh, 2009). The Pakistan Council of Appropriate Technology (PCAT) found that 74% of non-operational MHP schemes had a lack of community management (Junejo, 1997).

Community's active participation: the active participation of the community during the construction of the civil works of the scheme is the first step into engaging the community with the operation and maintenance of the scheme. The construction and repair of the scheme gives the community a sense of empowerment and ownership. Moreover, the use of local workers and managers greatly reduces the project costs (Harvey et al., 1993). A study found an increased rate of success in MHP schemes when communities contributed with local labour (Paish, 2002).

A MHP scheme is a complex engineering solution for traditionally agricultural communities, and its implementation can generate a problematic technological gap. The active participation of communities in the educational workshops provided by developers can help reduce such gap.

iii. Environmental factor

Environmental impacts: the lack of a dam in a RoR system greatly reduces environmental impacts (Singh, 2009). However, some researchers have remarked some of the potential damages to the ecosystem such as sedimentation in case of weir use, reduced oxygenation of the water, or generation of noise (Paish, 2002). A study on environmental indicators of MHP schemes showed that lower ecological footprint, area allocation, and lower overall environmental damage were some of the reasons why India has fostered RoR systems (Kumar et al., 2014).

Multiple environmental impacts are associated with the construction of RoR MHP schemes:

1. Harmful gas emissions to the biophysical environment, including greenhouse gases from construction machinery.
2. Civil works waste.
3. Noise generated by construction equipment.
4. Occupation of land for construction purposes.

A number of post construction environmental impacts have been identified:

1. Noise contamination due to the sound produced by the turbine and generator.
2. Visual impact due to modification of landscape.
3. Modification of water quality due to sedimentation.
4. Alteration of river biodiversity due to disruption of the water flow.
5. Maintenance waste products.
6. Reduction of noise and emissions from stopping usage of fossil fuel generation.

To mitigate noise coming from generation group, all the equipment tends to be contained in the powerhouse, something especially important when the powerhouse is in the village.

iv. Economic factor

Economic support and sustainability: one of the disadvantages of MHP technology is its high capital cost. In most scenarios, communities are not able to afford the design and construction costs, and the implementation of a scheme is only possible with the help of external financial support. For successful rural electrification, government subsidy programs play an essential role (Gurung et al., 2011). Projects with a lack of financing tools, NGOs contribution, governmental help and community involvement have experienced much higher failure rates (Smith, 1994).

The contribution to the initial cost of the scheme is an important step towards engaging the community with the scheme. A study showed an increased rate of success in MHP schemes when the community committed to contribute economically to the creation of the scheme (Paish, 2002).

A great reduction of the total cost of the project can be achieved through community engagement (Smith, 1994):

- Community production capabilities (nearby sources of construction materials and manufacture power).
- Community scheme operators and administrators.
- Community capacity towards economic organization. Experience with past and ongoing communal projects.

During the lifetime of schemes, these can suffer failures in the civil works and the generation group. Often the repairs needed can be very costly, especially when landslides break scheme sections, or when the turbine or generator require replacement. The capacity of the community to economically contribute to the repair of the scheme is key to guarantee the economic sustainability of the scheme. In Northern Pakistan, the Aga Khan Rural Programme installed 15 schemes; in all cases villagers contributed to labour, in some cases villagers also contributed with funds. The cases with fund contribution turned out to be more successful (Smith 1994).

Increasing stakeholder involvement can be key for the economic sustainability of MHP schemes. The creation of businesses (i.e., end-uses) depending on the electricity generated by the scheme creates revenue and helps guarantee the constant functioning of the scheme (Paish, 2002).

Political factor

The installation of MHP schemes often requires the agreement of the local governmental authorities. Any engineering project subject to regulations, policies and laws, will see its feasibility and likelihood of success affected by the stability, modernity and administration capabilities of the country (Gurung et al., 2011).

If a scheme can connect and sell electricity to a national grid, this can create extra revenue, which can have a very positive impact in the economic sustainability of the scheme, and create extra revenue for the community. Countries with policies that allow MHP grids to be connected to the national grid for selling electricity, are more prone to construct MHP plants (Smith, 1994). Revenue generated by the sale of electricity back to the grid can be used for scheme repairs or upgrades, thus increasing the scheme economic sustainability. MHP schemes in developing countries, however, do not have the electric equipment to do such connection safely, and consequently, local electricity companies are unwilling to connect to MHP schemes, even if local policies allow it. In Nepal, specific policies allow MHP schemes to sell back to the grid, however, only a few unsuccessful initiatives exist in the country. Thus, when the national grid arrives to communities, the MHP scheme cannot sell electricity back to the grid, and communities swap to the more reliable national grid and abandon the MHP scheme.

The political factor has thus been not considered in this study as a key factor towards the success of schemes, as the arrival of the national grid can result in the success or in the failure of schemes, regardless of current local policies.

2.5 Chapter summary

MHP is a well-known technology with great potential in developing countries such Nepal, Bolivia, Cambodia or the Philippines. However, despite the overall good efficiency and power generation capacity of hydropower technology, community owned MHP schemes struggle to operate trouble free and suffer efficiency loses and scheme failures often. Current pre-feasibility assessment methods are too simplistic and ignore key factors. A multi-criteria decision making method such as the analytic hierarchy process can be used to create a pre-feasibility assessment tool that can integrate the factors that affect the likelihood of success of schemes. Thus, gaps in current knowledge exist that need to be addressed:

1. The reasons behind the failure of schemes are not well understood. The variety and quantity of failures that schemes suffer has not been properly evaluated.
2. No databases exist on the current state of MHP schemes in developing countries.
3. The livelihood impact that the implementation of a scheme has on a community has not been well studied.
4. No holistic pre-feasibility assessment tool exists that integrates the four factors (physical, social, environmental, economic) that affect the likelihood of success of schemes.

3. MHP Success and failure reasons and scheme current success score framework

3.1 Introduction

Micro-hydropower, understood as the generation between 5 and 100kW, can be a cost-effective solution for the production of energy for small isolated communities (Maher et al., 2003, Blanco et al., 2008, Mainali et al., 2013, Huang et al., 2014). Positive environmental benefits as well as socio-economic advantages of community owned MHP schemes are widely recognized (Paish, 2002; Pokharel et al., 2008; Gurung et al., 2011). MHP has also been adopted as a means to foster rural development with the help of the "free energy from water" motive (Murni et al., 2013). Furthermore, communities built around streams in mountain areas often meet the necessary requirements of water head and flow. These well documented reasons to adopt MHP have lead developers to install schemes, but often with insufficient consideration for the performance and longevity of the scheme after its installation (Fulford et al., 2000, Kabalan et al., 2014).

Nepal, with its rugged mountains and extensive hydrological resources, is the leading country on community owned MHP, with 1152 schemes built since 1962 and 22830kW installed (Nepal Ministry of Finance 2015). Nepal's MHP development success is based on the foundations of pro-active governmental institutions, local expertise and a strong private sector, which have resulted in significant socio economic advantages for MHP in Nepal (Pokharel et al. 2008, Gurung et al., 2011, Mainali et al., 2013). Fifty percent of each MHP project cost is subsidized by the government and thirty percent is often provided by district government to account for the fact that Nepal's national electricity grid expands at a very slow rate due to difficult geographic characteristics. The Nepali MHP scene has been subject to numerous studies and has set standards that have been employed around the world (Paish 2002, Chitrakar 2004, Pokharel et al. 2008).

Bolivia and the Philippines have seen the construction of approximately a hundred MHP schemes each since the mid-90s. In a study of 8 rural communities in Bolivia, governmental bias towards a central electricity grid and the lack of local financial and technical expertise were identified as the main factors hampering MHP development in the country (Drinkwaard et al., 2010). Geographic characteristics in many parts of Bolivia, however, are ideal for MHP and in a study of 9 different MHP schemes in Bolivia, communities showed significant enhancements in living conditions, such as education, health and comfort (González et al., 2009). The Philippines, a country with extensive hydrologic resources, has numerous inhabited islands of volcanic origin, making the expansion of the national grid highly costly, but ideal for the creation of local MHP schemes (i.e. steep terrain). The two countries, however, suffer from a lack of governmental support for MHP, where no consistent subsidy system exists. The local expertise extends to a handful of NGOs dependent on international aid. There is no capability in private commercial industry to build schemes or manufacture machinery, forcing local developers to import equipment, hence increasing scheme cost.

In Cambodia, MHP development is in its most basic stage, even though good sources of water throughout the plains and hilly areas provide the necessary physical conditions for small scale MHP. There are presently no governmental or non-governmental organizations installing MHP schemes and governmental support or subsidy systems are inexistent. However, a few schemes based on local entrepreneurial initiatives exist in the country's Cardamom mountain range. There is no available literature on MHP in the country, making this study the first of its kind for Cambodia.

A number of detailed MHP design and installation guides have been written (CANRen 2004, Singh 2009), and several best practice guidebooks and papers are available on the installation and operation and maintenance of schemes (Smith 1994, Fulford et al., 2000, Khennas et al., 2000, Mohibullah et al., 2004, Blanco et al. 2008). However, there is a lack of research into existing but non-functioning schemes and the reasons behind their failures. To evaluate the level of success, failure reasons must be analysed. Multiple studies exist on the analysis of the status of few MHP schemes in a single country, but with no quantification of system failures. A study of 3 MHPs in the Philippines found that the experience of the installing organization, its capacity to balance installation costs with scheme performance, and addressing social issues were fundamental for the success of schemes (Kabalan et al., 2014). The most complete study available on MHP in developing countries, with 16 schemes studied in Zimbabwe, Mozambique, Sri Lanka, Peru and Nepal, found that properly identifying the purpose of the scheme and building it according to its task and location are critical factors for the success of a MHP scheme (Khennas et al., 2000). A study conducted in Malaysia of six communities concluded that to be able to create realistic MHP installation guidelines to satisfy the needs of rural communities, more research is required into understanding the success factors of MHP (Murni et al., 2013). Furthermore, no research, published or otherwise, has been found proposing a system to evaluate the current level of success of an installed scheme.

The objective of this study is thus to identify the Key Variables that indicate the level of success of a scheme from the communities' point of view. Following the identification of Key Variables, the development of a framework to evaluate the current level of success of installed schemes across countries is proposed with the aim of enhancing knowledge of MHP development.

3.2 Methods

3.2.1 Research methodology

This study is based on the evaluation of 35 schemes across Nepal, Bolivia, Cambodia and the Philippines during 2015 and 2016. For each country, relevant local developers were contacted to obtain detailed information on country specific MHP characteristics, current MHP development barriers and limitations, funding systems, and policies. Informal interviews with developers provided additional information on known MHP schemes, technical characteristics, and community socio-economical characteristics. Community owned schemes were selected for site visits by considering their characteristics, operational state, location, and ease of access. The schemes selected contained a variety of power production levels, household numbers, end-uses (productive use of the energy), location (geophysical characteristics), years in operation, and overall scheme performance (Table 8).

The schemes selected for site visits fell under the micro-hydro category, with the exception of Nep.10, Bol.3, Cam.5, Cam.6 and Cam.7, which have a power production lower than 5kW.

Table 8. Synopsis for the Nepalese, Bolivian, Cambodian and Philippines schemes visited

Scheme	Years Operating	Households	Productive End-uses	Turbine	Region	Head (m)	Flow (l/s)	Power (kW)
Nepal								
Nep.1	2	745	0	Crossflow	Hills	70	240	86
Nep.2	5	179	5	Crossflow	Hills	13	216	17
Nep.3	4	140	2	Pelton	Hills	210	15	16
Nep.4	15	272	11	Crossflow	Hills	54	100	26
Nep.5	12	230	6	Crossflow	Hills	17	120	10
Nep.6	16	158	3	Pelton	Hills	58	70	22
Nep.7	10	115	6	Crossflow	Hills	58	45	15
Nep.8	4	133	2	Crossflow	Hills	16	162	12
Nep.9	16	290	7	Crossflow	Hills	32	150	24
Nep.10	17	11	1	Turgo	Hills	3	45	1
Bolivia								
Bol.1	7	25	0	Pelton	Andean	50	50	6
Bol.2	2	14	2	Pelton	Andean	55	25	8
Bol.3	2	1	1	Pelton	Andean	40	25	2
Bol.4(nf)	8	80	0	Pelton	Sub-Andean	166	84	100
Bol.5(nf)	14	30	0	Pelton	Sub-Andean	134	20	16
Bol.6(nf)	12	40	0	Pelton	Sub-Andean	96	15	8
Bol.7(nf)	6	120	0	Pelton	Sub-Andean	73	90	38
Bol.8(nf)	11	180	0	Pelton	Llanos	81	80	40
Bol.9	1	60	4	Crossflow	Sub-Andean	36	180	35
Bol.10	7	313	0	Crossflow	Sub-Andean	126	170	100

				Cambodia				
Cam.1(nf)	5	5	1	Propeller	Plains	2	1000	12
Cam.2	5	25	1	Propeller	Plains	2.5	1300	8
Cam.3	11	4	1	Propeller	Plains	2	1000	10
Cam.4	5	80	0	Propeller	Cardamom	10	800	40
Cam.5	2	1	0	Propeller	Cardamom	3.5	16	0.6
Cam.6	5	1	1	Propeller	Cardamom	5	30	0.5
Cam.7	2	12	0	Propeller	Cardamom	2.5	200	3
				Philippines				
Phi.1	7	58	0	Crossflow	Cordillera	80	25	15
Phi.2	9	14	1	Crossflow	Cordillera	43.5	20	5
Phi.3	14	43	2	Crossflow	Cordillera	52	20	6
Phi.4	16	52	1	Crossflow	Cordillera	10	120	7
Phi.5(nf)	6	100	1	Pelton	Negros Island	105	44	34
Phi.6(nf)	5	30	2	Water mill	Negros Island	1.5	500	5
Phi.7	8	200	0	Crossflow	Negros Island	18	2750	28
Phi.8	8	150	0	Crossflow	Negros Island	79	50	22

(nf) – Not functioning

The socio-economic characteristics of all the studied communities were similar, with agriculture being the base of their economy and subsistence. While cultural values, languages and traditions were different, they shared the willingness to adopt and benefit from MHP technology.

During the site visits, a structured interview to one or several key members of the community provided qualitative and quantitative information on the actual performance of the scheme in regards to its power generation, water availability, operation and maintenance, environmental and social effects, community power demand, and community perceived value of the scheme. A semi-structured interview with present and past operators and key members of the MHP committee was conducted on site, while directly observing each one of the elements of the scheme, from water intake to electric transmission. This allowed for the recording of past repairs, malfunctions, replacements and present glitches as well as current maintenance requirements.

This research used a learning-based approach to combine all sources of information to identify the criteria and Key Variables for the development of the success framework.

3.2.2 Scheme Success Framework development

If success is to be measured, first it needs to be defined. Success can be defined as the degree to which a purpose or aim is achieved. A MHP scheme, however, can accomplish different types of purposes. MHP can be a means for a community to achieve electrification. Some schemes are designed to partially or totally meet the energy needs of an enterprise, and its success should therefore be analysed in regards to its specific objective (Khennas et al., 2000). This study defines MHP success as the measure to which a scheme has accomplished its purpose of generating power while accomplishing a sustained livelihood improvement for the people of a community.

To evaluate the current level of success of a scheme, a scoring system based on the criteria defined in Table 9 was used. A set of Key Variables define each criteria. The framework had to be easy to use, and applicable to different schemes across countries. Consequently, the Key Variables suggested in Table 9 are the result of a screening based on two principles: 1) consideration of the level of importance of the variable affecting the success of the scheme 2) easiness of acquiring such information. The scheme Success Score is a function of the sum of the values given for each Key Variable.

Table 9 MHP Scheme Success Framework

Criteria	Key Variables		Score
1. Power generation The power generated needs to be consistent with the power projected, allowing for small seasonal and operational variations.	1.1	Power generated	[0,2,4]
	1.2	Water availability	[0,2,4]
2. Operation and maintenance The scheme maintenance needs to be consistent and adequate, allowing for only short periods of downtime for repairs and replacements.	2.1	Maintenance status	[0,1,2]
	2.2	Scheme failures	[0,1,2]
3. Environmental damage Damage done to the environment during construction or operation of the MHP scheme needs to be minimal.	3.2	Environmental damage	[0,1,2]
4. Community approval The community needs to feel satisfied with the performance of the scheme and identify it as a positive input towards their livelihood.	4.1	Community satisfaction	[0,1,2]
	4.2	Community involvement	[0,1,2]
5. Sustainability All the preceding points need to be achieved throughout an extended period of time ideally matching the expected technical lifespan of the scheme. The number of years in operation is used to account for the current level of success of operating schemes.	5.1	Years in operation	# years

Detailed variable score allocation criteria is as follows:

1.1 Power generated: The power generated has to be equal or close to the design power. A decrease in the scheme performance over time is expected due to mechanical wear.

[0] – The power generated is less than 50% of the design power.

[2] – The power generated between 50% and 90% of the design power.

[4] – The power generated greater than 90% of design power.

1.2 Water availability: Water availability is a fundamental variable for power production. The lack of it is a nearly irreversible problem (in rare occasions a second intake can be added).

[0] – Water availability is insufficient to continuously generate desired power throughout the year.

[2] – Water availability is insufficient at specific periods of the year (typically dry season).

[4] – Water availability is consistently sufficient to meet the design levels all through the year.

2.1 Maintenance status: All civil works and powerhouse equipment require maintenance to ensure long term operation of a scheme. Tanks require regular emptying and cleaning, cleaning procedures need to be adapted to seasonal requirements (i.e. wet season is more maintenance intensive), and mechanical parts require periodic maintenance due to wear.

[0] – The scheme shows functional deficiencies and poor maintenance. Operator does not comply with the necessary periodic maintenance.

[1] – The scheme has some minor maintenance issues. Operator does not fully comply with the necessary periodic maintenance.

[2] – The scheme shows correct maintenance status. Operator complies with necessary periodic maintenance.

2.2 Scheme failures: MHP schemes have multiple parts that are exposed to wear, human manipulation and the surrounding environment, thus, failures are expected and machinery wear is inevitable. However, ongoing scheme failures are a symptom of a decaying scheme and a clear indicator of an unsuccessful scheme. Malfunctions in civils works, powerhouse and distribution can all create undesirable power cuts (failures).

[0] – The scheme has had one or more failures that left the scheme non-operative.

[1] – The scheme has had minor failures, but normal operation resumed within days.

[2] – The scheme has had no failures.

3.1 Environmental damage: Water intakes, channels, tanks and pipes can fail causing sediment and flow alterations leading to environmental impact to the surrounding area. The diversion of the stream can also damage the existing ecosystem of the stream, especially in dry season when the scheme diverts all the water for generation, resulting in dry stream bed between the intake and the MHP discharge point. Damage to the surrounding environment is not acceptable.

[0] – The scheme has caused irreversible damage to the surrounding environment.

[1] – The scheme that has caused damage to the surrounding environment.

[2] – The scheme has caused minimal damage to the surrounding environment. The natural stream flow is minimally affected by the scheme.

4.1 Community satisfaction: The management of community owned MHP schemes is done through community meetings in which all members of the community are stakeholders. From the community's point of view, operating a MHP scheme is a trade-off between having electricity and spending time and money on its operation. If the community feels not satisfied with such trade-off, disputes will arise during the community meetings, hampering the management of the scheme.

[0] – Members of the community express clear dissatisfaction with several aspects of the scheme.

[1] – Members of the community express dissatisfaction with some aspects of the scheme, yet the community is mostly satisfied.

[2] – Members of the community are satisfied with the scheme.

4.2 Community involvement: The community involvement in a scheme is a well-documented cornerstone of the success of a scheme (Blanco et al., 2008, Smith, 1994). The involvement of a community is an indicator of the will and determination of the community to keep on working towards the good functioning and continuity of the scheme. It is an indicator of the scheme resilience.

[0] – The community is clearly divided and the operation of the scheme is uncoordinated. A lack of collective meetings and personal disputes are common indicators.

[1] – The community shows signs of disputes between its members, but maintains collective meetings, keeps the structure of the MHP committee and continues operation of the scheme.

[2] – The community maintains scheduled collective meetings, keeps the structure of the MHP committee and coordinates operation of the scheme.

5.1 Years functioning: Due to the complex set of existing sustainability indicators and the difficulty of measuring them on site, the framework adopts a different approach, and measures the result of past achieved success directly, that is, the years the scheme has operated, an easy to measure and obtain indicator. The time a scheme has been functioning is the measure in which a scheme has proven its success and sustainability while accomplishing its purpose. One point per year of operation is allocated to account for its attained sustainability.

The allocation of one point per year of operation for the sustainability criteria is based on the rationale that a scheme that has lasted for many years is more likely to score lower values on the other 4 criteria. Similarly, a newly constructed scheme will easily have good scores in the first 4 criteria. With this understanding, a scheme will score overall high scores if it can meet criteria 1 to 4 for many years.

3.2.3 Assumptions and limitations

The five criteria chosen in this study are considered essential measures of the success of a scheme. The broad range of variables affecting MHP schemes success forces us to make assumptions when designing the framework:

- The framework does not consider national electricity policies or the possibility to sell electricity back to the grid and assumes the schemes to be legal and working independent to the national grid.
- The framework does not evaluate tariffs, operator salaries, and others, but incorporates economic aspects with the evaluation of measureable Key Variables such as the extent of operation and maintenance.
- The framework evaluates the estate of a scheme in its current situation, or until it has failed.
- The framework allows for the evaluation of an already existing scheme. It is not intended for evaluating the feasibility or success of future schemes.

The success criteria has been selected based on the data and experience gained during the site visits of a limited number of schemes per country. The framework is designed to be applied on-site. The variables considered require for the person applying the framework to be present at the scheme location.

3.3 Results

Results from the interviews and data collection showed that the process of MHP site identification, scheme design, installation and transfer of the scheme ownership to the community was very similar between Nepal, Bolivia and the Philippines. Workshops on energy awareness, electricity use, and operation and maintenance of schemes were given to the community. Administration techniques, tariff allocation and collection, and communal group discussions over scheme performance were also introduced to the community. Furthermore, in the schemes studied, a MHP committee consisting of a team of operators, a tariff collector and a president, managed the scheme. In Cambodia, no such implementation protocol exists, and schemes had a greater variety of community management approaches.

The information gathered for all MHP schemes visited in Nepal, Bolivia, Philippines, and Cambodia was applied to the MHP Scheme Success Framework (Table 10). Nepal, the country with more technical experience and economic resources had the highest total average score. The Philippines and Bolivia, countries that have followed the steps of Nepal in implementation methodology and construction techniques, follow in the list. Cambodia, with distinctively different scores to the other countries, falls in last position. Grouping the results of the framework's success into bands, the differences between countries become clearer (Table 10).

Table 10. Average and standard deviation (in parenthesis) values for the Key Variables of the MHP Scheme Success Framework for each country.

Country	Num. Schemes	1.1 Power generated	1.2 Water Avail.	2.1 Maint. status	2.2 Scheme failures	3.1 Environ. Damage	4.1 Comm. Satis.	4.2 Comm. Involv.	5.1 Years in operation	Total
Nepal	10	3.4 (1.3)	3.4 (1.0)	1.9 (0.3)	0.2 (0.4)	1.1 (0.9)	1.6 (0.5)	1.5 (0.5)	10.1 (5.9)	**23.2 (6.2)**
Bolivia	10	3 (1.4)	1.6 (2.1)	1.8 (0.4)	0.4 (0.7)	0.9 (0.9)	1.6 (0.5)	1.7 (0.7)	7 (4.4)	**18 (3.5)**
Cambodia	7	1.7 (0.8)	2.0 (2.0)	1.0 (0.8)	1.4 (0.8)	1.4 (0.5)	1.4 (0.5)	1.6 (0.8)	5.0 (3.0)	**15.6 (4.8)**
Philippines	8	3.5 (0.9)	3.0 (1.5)	1.6 (0.7)	0.5 (0.8)	1.6 (0.7)	1.6 (0.7)	1.3 (0.7)	9.1 (3.9)	**22.3 (5.8)**
Total Ave.		**2.9 (1.3)**	**2.5 (1.8)**	**1.6 (0.6)**	**0.6 (0.8)**	**1.3 (0.8)**	**1.6 (0.6)**	**1.5 (0.7)**	**7.8 (4.8)**	**19.8 (5.8)**

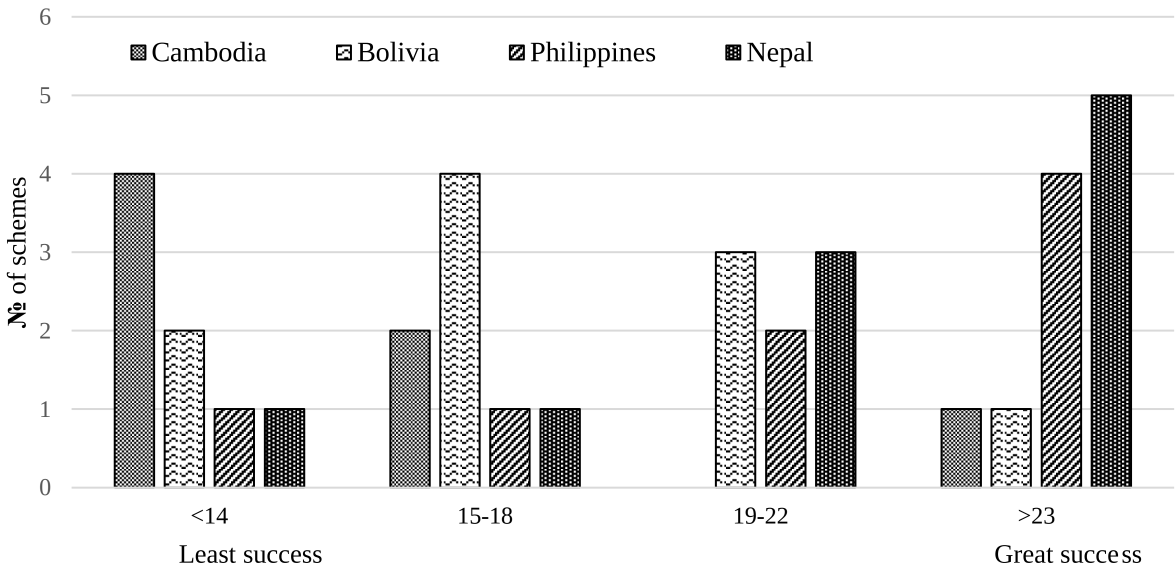


Figure 6. Number of schemes classified by score in the Scheme Success Framework for Cambodia, Bolivia, Philippines, and Nepal.

Power generation (Key Variables 1.1, 1.2)

Formal interviews with the operators revealed that most schemes produced the amount of energy needed at the moment (Total Ave 2.9). Some of the schemes managed to maintain high levels of power throughout time because the MHP scheme was under-designed (i.e., the amount of available water and head could generate more power). However, with time, all schemes suffered some degree of efficiency reduction due to wear of the electromechanical equipment. In some scenarios, where the water couldn't be adequately de-silted and cleaned of debris, turbines suffered severe degradation thus reducing power generation. Degradation damage was more likely during the wet season, where strong weather events increase water turbidity and foliage deposition along the headworks. Cambodian schemes underperformed (i.e. score of 1.7) because the installation of the penstock, turbine and generator was technically deficient.

The scores of water availability varied from country to country according to how annual stream flow patterns were estimated. For a scheme to be designed for the correct flow volumes, it is fundamental to have accurate flow duration curves (FDC) (Blanco et al., 2008). None of the countries had accurate FDC's, as river gauging proved expensive, technically challenging, and time consuming. Nepal (3.4), with the highest score, uses a salt dilution method (Harvey et al., 1993) coupled with a national climate database for estimating flows over time, and particular emphasis is placed on estimating the lowest flows of the year. The Philippines (3.0) and Bolivia (1.6) use a combination of on-site monitoring methods (bucket, float method, current meters) and information from nearby gauged streams to estimate annual flow patterns. In Cambodia (2.0) schemes are designed by local farmers who rely fully on site visual observations.

Operation and Maintenance (O+M) (Key Variables 2.1, 2.2)

The schemes analysed in Nepal (1.9), Bolivia (1.8) and the Philippines (1.6) showed high levels of commitment towards adequate maintenance of the schemes. In these countries O+M workshops were given to communities before the installation of the scheme. Most schemes had two trained and paid operators who maintained both civil works and powerhouse, although other members of the community would assist on maintenance duties when required. When major damage occurred to the civil works, the whole community would assist on the restoration process. In Cambodia, where schemes had much smaller head, the operation and maintenance was significantly different. Schemes had no headrace or forebay tank, and turbines were propeller type, a situation that generated less maintenance necessities (i.e. no need to forebay tank cleaning, extended turbine life, and less greasing required due to lesser shaft speed).

A high level of adequate maintenance was observed, (Total Ave. 1.6), yet the number of scheme failures was high (Total Ave. 0.8). Failures were considered as mishaps that left the scheme part unusable. The failures of five different powerhouse elements were recorded, as well as the six most common civil works related failures (Table 11).

Table 11. Number and type of critical failures for the analysed schemes.

		Powerhouse						Civil works							
Country	Num. Schemes	Electronic load control	Energy dissipater	Turbine	Generator	Transmission lines	Sub-total	Intake	Headrace	Tanks	Penstock	Landslides	Spills	Sub-total	Total failures/ scheme
Nepal	10	7	1	1	3	0	12	2	0	1	0	2	1	6	1.8
Bolivia	10	3	3	4	4	2	16	2	4	3	2	4	5	20	3.6
Cambodia	7	1	0	0	2	0	3	2	0	0	0	0	0	2	0.7
Philippines	8	3	1	1	2	0	7	4	4	0	0	5	3	16	2.9
Total	35	14	5	6	11	2	38	10	8	4	2	11	9	44	2.3

The average rate of failures per year in Nepal is 0.36, in Bolivia 0.83, Cambodia 0.23 and the Philippines 0.38. On average, schemes suffered 2.3 failures over lifespan and civil works failures were 16% more common that powerhouse failures.

In the powerhouse, the electronic load control (ELC) was the element reported to fail the most often (Table 11). ELCs are costly (approximately 100USD/kW) and are too complicated to repaired for communities. 11 of the 35 schemes visited did not have an ELC, which means 58% of all schemes with ELC failed at some point. Regrettably, powerhouse failures were found to have a very high cost, often leaving the community unable to repair it by themselves.

On the civil works side, destroyed intakes and landslides were the main failures reported, which were a result of strong weather events. Severe storms generate flush floods that can carry heavy objects that can impact against the intake structure. Persistent rainfall penetrating into deeper soil layers can also trigger landslides which cause blockages and destroy civil works structures. The vast majority of intake, canals and tank damages can be repaired by the community, a process that exhausts local materials and uses community labour time.

Nepalese civil works appear more robust and technically adequate than in Bolivia or the Philippines. Local expertise and better economic resources meant better design and more robust structures. In Cambodia, schemes are placed in flat areas, often fed by underground spring water, with no risk of flush floods or landslides. Furthermore, the propeller type turbines used, spin slow and are more robust. Six of the seven visited schemes had no electronic load control. Overall, the low head MHP scheme setup in Cambodia proved to be very reliable.

Environment damage (Key Variable 3.1)

The schemes visited in this study showed moderate environmental damage (1.3). Site observations showed that headrace water leaks or headrace overtopping due to bad operation of the powerhouse valves was a common cause of localized environmental damage by erosion. Moreover, environmental damage was reported in Nepal and Philippines whereby electricity generated by the MHP was used to kill fish by electro fishing (i.e., introduction of two anodes connected to a battery in the river), resulting in the unnecessary death of surrounding aquatic organisms. These examples, however, were few and the overall environmental impact was deemed small or difficult to ascertain.

Community approval: (Key Variables 4.1, 4.2)

Results show very similar scores of satisfaction levels for the studied schemes. Communities expressed dissatisfaction with power reliability, arguing that the extended downtime periods were highly detrimental to them. Communities also expressed concerns with power availability, as they saw that power generation was decreasing (i.e. power losses due to scheme aging) at the same time that community power demand was increasing (i.e. higher consumption per household and/or higher number of households). Such situation often left communities with limited power availability during demand peak hours. Nevertheless, very few communities expressed disdain towards their scheme. A great sense of gratitude towards having electricity through their MHP scheme was present in almost every community.

Community involvement with schemes where overall high (1.5). Communities across all countries felt that their MHP scheme was a key part of their village. The communal management of the scheme gives them a sense of empowerment and autonomy. In some communities, however, the MHP committee would take control of the decision making process with little extended community input. When schemes were having technical problems, however, the community would blame the operators and MHP committee without fully understanding the technical problems.

Scheme sustainability (Key Variable 5.1): The schemes visited in this study ranged from newly built schemes, to schemes that were exceptionally long lasting. Remarkably, 5 schemes were more than 15 years old. The expected lifespan of the electromechanical equipment is much shorter, with most elements failing between 5 and 10 years. Communities often do not manage to save enough money through their monthly tariff to replace elements of the powerhouse. The average age of the non-functioning schemes was 8.4, with four of the eight schemes failing due to maintenance difficulties hampered by economic hardship (Table 12). Although a detailed analysis on the economic sustainability indicators was not performed, communities claimed that the provision of funds collected by the community as part of their tariff payment proved to be insufficient to afford the cost of repairing critical scheme damage. Interestingly, however, communities showed great opposition to the proposal of rising their monthly tariff.

This study purposely selected schemes that were no longer operational to understand the reasons that force MHP schemes to stop operating. When analysing the scores on scheme sustainability and final Scheme Success Framework score, it has to be taken into account that in Bolivia five of the ten schemes analysed were no longer operating, while in the Philippines only two were not operational, in Cambodia only one, and in Nepal all of the schemes analysed were operational. The main reasons for the failure of the non-functioning schemes were the arrival of the national grid, maintenance difficulties, and failures related with extreme weather events (Table 12).

Table 12. Years of operation of non-functioning schemes and failure cause.

Scheme	Years Operating	Failure cause
Bol.4(nf)	8	Maintenance difficulties, severe landslide.
Bol.5(nf)	14	Arrival of national grid.
Bol.6(nf)	12	Maintenance difficulties, water availability, arrival of national grid.
Bol.7(nf)	6	Severe landslide.
Bol.8(nf)	11	Maintenance difficulties, arrival of the national grid.
Cam.1(nf)	5	Scheme dismantled due to future flooding of area for mega hydro.
Phi.5(nf)	6	Maintenance difficulties.
Phi.6(nf)	5	Arrival of national grid, economic struggle.

3.4 Discussion

Power generation

Developers build schemes to satisfy the needs of a community at a specific moment in time; however, over time, households start overusing power, limiting other households' consumption, and creating conflict in the community. If power per household is to be maintained, limits should be imposed by the local developers. Communities, however, scared of capping their electricity consumption, refuse to establish limits on power consumption per household. Furthermore, the more development electricity brings to a community, the higher likelihood of new users arriving to the community to make use of electricity. In general, communities believe that the access to electricity for newly arrived households should not be denied. However, it is recommended that if additional households connect, a surplus of power must exist, and that the new household must compensate the community through payment of a tariff or other form of contribution.

Machinery and civil works deterioration reduces power availability. While sometimes it is possible to add an extra water intake (from another stream) or replace powerhouse machinery to increase efficiency, the majority of the schemes studied in this research did not have the potential to increase generation due to lack of available water and/or economic limitations.

Lack of water during dry months is a common problem reported by communities. If no systematic and reliable system to estimate river annual minimum water level exists, it is recommended to adopt a very cautionary approach when assuming the lowest annual flow. Further research is needed to understand if extended draught periods due to climate change will impact MHP scheme success.

Operation and Maintenance

The most reported source of frustration by communities was the number and length of scheme downtimes. Extended downtimes are often a product of replacement equipment unavailability and distance to closest repair workshops and urban centres, facts already reported in a study in Nepal and Sri Lanka (Fulford et al., 200). In Nepal, 3 of the studied communities could choose between national grid and MHP, the former being up to three times more expensive and with scheduled power cuts of up to 14 hours a day, yet, the majority of people preferred the national grid for its reliability during operation.

Developers in Nepal, Bolivia and the Philippines provide communities with a set of workshops covering electricity awareness and technical information on the operation and maintenance of the scheme. However, such educational process is often conveyed amidst cultural and language barriers, and with the passage of time and manpower turnover, knowledge is inevitably lost (Drinkward et al., 2010). Adequate training to manage, operate and maintain the scheme is therefore necessary to prevent the decay of a scheme (Khennas et al., 2000). The Nepalese policy of forcing the scheme to be maintained only by qualified operators (typically 2) seemed more effective than the Bolivian and

Philippine flexible approach, which provides for widespread community involvement with the scheme, but results in a less technically effective maintenance.

Monthly tariffs collected for the operation and maintenance are often insufficient. Developers, in an attempt to help all members in the community (including those with lower economic resources), struggle to make households pay the minimum tariff to guarantee the scheme survivability, and often allow the community to decide how much they should pay. The outcome is that communities agree on an insufficient tariff.

Funding organizations provide economic aid for the construction of the scheme, yet do not provide funds for ongoing post-construction support. Developers that are able to install MHP schemes in Bolivia and Philippines do not have the economic and logistic capacity to provide the follow-up supervision program for each installed scheme. The experience in Nepal showed that the presence of strong stakeholders (end-uses) with mechanical and electrical knowledge in the community can attend to operation and maintenance challenges, increase load factor, reduce power plant downtime, and extend the economic and technical sustainability of the scheme. The experiences of this research show that without the existence of an external organization with economic and technical resources to provide continuous assistance, the technical sustainability of a MHP scheme in a remote community is at high risk.

Environment damage

Site visits and interviews showed that the installation of MHP schemes did no major damage to the environment. Several authors have even reported that the use of MHP can have beneficial effects to the environment because they are often used in place of polluting diesel generators (Pokharel et al., 2008, Gonzalez et al., 2009). However, of the 35 MHP visited in our study, only five of the communities had a diesel generator prior to the arrival of the MHP scheme, and these were later used as a backup sources. The arrival of MHP in communities also reduces the use of batteries, resulting in fewer batteries being improperly disposed.

A number of measures can be implemented to prevent or mitigate environmentally adverse impacts. Robust civil works and more adequate maintenance duties can mitigate landscape alterations (erosion) due to scheme failures. Incorporating lessons on river biodiversity during the scheme implementation process can help communities understand the importance of stream aquatic biodiversity, thus possibly dissuading electro fishing. Appropriate hydrology data, and applying intake design techniques that limit the maximum water that can be diverted from the stream, can mitigate stream impacts during the dry season.

Community approval

The communities studied showed good levels of satisfaction and villagers were positively involved with the MHP scheme. The pillars of such involvement were strongly set during construction of the scheme. Developers in Nepal, Bolivia and the Philippines implemented schemes giving equal opportunities to all members of the community and promoting active participation in the decision making processes. However, a question that should be raised is whether such opportunities can be equally taken by all members of the community. Gender, age, education, ethnic group, or economic status are factors that affect the capacity to take such opportunities.

However, most people interviewed expressed high pride and satisfaction on the active participation of the construction of the scheme. Some people justified that the scheme should be kept and maintained because "it was theirs, they built it". In the site visits it appeared clear that the impact of the construction of a MHP scheme goes beyond the electrification of households. Communities discovered, through the construction, powerhouse start up, and maintenance of the scheme, that they could build something that would benefit everyone and that such thing that appeared incomprehensible and out of reach, namely generating electricity, was something they could understand and harness.

Disputes over repairing methods and individuals responsibilities, however, were not uncommon. With the passage of time, influential community members with more experience with the scheme would tend to create small decision making groups, leaving aside the community, setting up the basis for discomfort by some. Moreover, when scheme failures occur, communities find themselves immersed in conflicts that they have no experience in solving. Thus, in order to maintain an efficient and egalitarian MHP committee, the local developer should maintain ongoing engagement with the community.

Scheme sustainability

With the arrival of energy, the community reaches a new lifestyle plateau. Small enterprises become reliant on the continuous generation of electricity and energy passes from being a commodity to a necessity. For the new asset to become a positive and sustainable input for the community, and not a burden, it needs to last.

Our results show that the average scheme durability is far lower to what previous publications have reported. A study based on UK suggests that schemes have low O&M and an economic life of 30 years for the powerhouse and 60 years for civil works (Kirk, 1999). Under the developing country scenario, studies suggest that schemes can last for 50 years without refurbishing (Singh, 2009, Paish 2002). More modern papers echo such observations (Gurung et al., 2011). The results and observations of this research do not share such optimistic observations since, in most schemes, scheme failures occur in much shorter intervals of time, with most parts of the electro-mechanical equipment lasting between 5 to 10 years.

A study in Peru observed that the key question for local developers was “how long will the plant last?” (Khennas et al., 2000). Interviews with developers revealed that it is not economically feasible to build schemes that could safely withstand floods or landslides. The lifespan of the powerhouse machinery can meet the 20 years benchmark, as long as the maintenance is done adequately and new installed parts are well built and mounted. Such assumptions are unrealistic in the community owned MHP model.

The economic sustainability of the studied schemes was poor. Communities fail to agree with local developers on a tariff that is sufficient to guarantee the survivability of the scheme. To prevent the failure of schemes due to lack of funds for repairs, it is recommended that developers impose a tariff system or incorporate some critical maintenance costs within the original build budget.

3.5 Conclusions

The results of this research show that the success of community owned MHP schemes is compromised by several factors. Communities showed significant difficulties to maintain their schemes while producing the desired power levels. 16 of the 35 schemes showed poor levels of water availability during the dry season because economic limitations do not allow for the necessary hydrological studies to properly calculate long term river flows.

The lifespan of critical components of schemes proved to be significantly inferior to what previous literature has stated. Overall, the results of this study show that the technical, social and economic survivability of community owned MHP schemes is very fragile, with schemes suffering an average of 0.47 critical failures per year. Our results show that the Nepalese governmental programs of financial and technical support are an effective way to help MHP schemes operate more successfully and for longer.

The major factors that influence MHP downtimes and system failures across all countries were:

- Maintenance difficulties due to insufficient community management and maintenance capabilities and insufficient provision of funds for repairs and replacements.
- Severe weather events damaging civil works and powerhouse machinery.
- The arrival of the national grid, preferred for its reliability despite its higher cost.

The following factors were identified as the most important for the long term success of schemes:

- Proper maintenance and operation carried out by at least two well trained and well paid operators.
- A realistic monthly tariff to generate sufficient provision of funds for operations/maintenance.
- Ongoing community support through a strong long lasting committee.
- External long term technical and economic support from developers and governments.

No framework to evaluate the success of schemes exist nowadays, thus, the framework proposed is a necessary step towards evaluating scheme success levels. The application of the framework demonstrated that Nepalese schemes achieved higher scores due to better construction techniques, local maintenance and manufacture capabilities, and governmental technical and economic ongoing support. The framework can be further enhanced by adding the necessary variables to adapt to country specific MHP necessities. It is recommended that this framework be applied to help developers and governments evaluate the status of MHP schemes in different countries and generate national and international databases on scheme success levels.

4. MHP impact on communities' livelihood analysed with the capability approach

4.1 Introduction

Access to electricity is one of the cornerstones of human development (UNDP, 2001). The lack of access to electricity in remote areas in developing countries has been identified as a key factor that jeopardizes progress towards better livelihoods (Gurung et al., 2010). The electrification of households can produce improvements in health, safety and education. It can also promote the creation of small enterprises or boost the production and efficiency of existing ones, reduce drudgery, lower the cost of lighting and other energy services and provide higher levels of comfort to its beneficiaries (Bastakoti, 2006). Electricity is, thus, a means towards achieving economic growth, social progress and increased human well-being (understood in this study as the individual state of comfort and happiness).

Micro-hydropower (MHP) schemes can produce electricity for isolated communities who are not connected to national electricity networks. The implementation of a MHP project is a cost-effective solution that has less environmental impact than traditional fossil fuel generators (Huang et al., 2014, Mainali et al., 2013).

MHP can bring to communities many advantages that stem from the generation of electricity. Several socio-economic advantages have been associated with the installation of MHP projects, such as extended income generating activities thanks to electric lighting, the reduction of drudgery (especially significant for women), or the increased production of local labour thanks to advanced machinery (Gurung et al., 2011, Paish, 2002). The arrival of electricity also brings numerous livelihood improvements to communities, such as increased education, added socializing opportunities and "improved general health conditions" (Gurung et al., 2010). A study done over 9 communities in Bolivia, revealed increases in night-time study, better health services, better access to telecommunications and a cost reduction in energy services (González et al., 2009). Improvements in livelihoods are often more significant than community and household economic development (Murni et al., 2013). MHP may thus foster economic development and increase community livelihood (understood in this study as the means to secure living necessities).

Measuring livelihood improvements, however, presents multiple challenges. The problem of measuring livelihood has been historically tackled by quantifying assets and income generation activities. However, recent studies suggest income based analysis are insufficient. Studies in Chile and Peru showed that the relation between income generation and indicators such as health, schooling and child nutrition was highly "non-linear" (Robeyns, 2006). Remote communities in developing countries are often driven by cultural dynamics where material assets may not be as important.

The "capability approach" framework offers an alternative approach to income based analysis (Robeyns, 2005). The framework uses freedom of choice to measure a person's well-being. The measure of what a person is capable of being (happy, healthy, educated) or doing (work, study, speak, walk) are called 'functionings' and they "represents the diverse aspects of life that people value" (Alkire, 2005). The premise of this framework is that the well-being of an individual should not be based on resources, justice or development level, but on the effective opportunities that people have to lead the lives they have reason to value (Sen, 1999).

Two developing countries where remote communities are in need of MHP are Bolivia and the Philippines. Both countries have good hydrologic resources and steep mountain ranges that have allowed for the construction of over a hundred MHP schemes in each country since the mid-1990s. The socio-economic characteristics of remote communities in these countries, where basic food and education needs are generally covered, have made the arrival of electricity a necessary step towards development. However, community owned MHP schemes suffer a lack of governmental support. The design, machine manufacturing, civil works construction and management of MHP schemes are done by only a few NGOs funded by international aid. The construction and maintenance of schemes is done under limited economic support and technical know-how.

Previous studies suggest that the sustainability of community owned MHP projects in developing countries is limited and dependant on technical, environmental, economic and social factors. A study in the Philippines over four MHP schemes concluded that a lack of technical know-how from communities and developers as well as deficient financial administration hinder the sustainability of schemes (Kabalan et al., 2014b). A study of 35 schemes between Nepal, Bolivia, Cambodia and the Philippines showed high scheme failures rates due to maintenance difficulties and severe weather events, and classified the average sustainability of schemes as "poor", with schemes seldom surviving more than ten years (Arnaiz et al., 2018).

MHP schemes in remote villages in developing countries are operated and managed by communities. During the implementation process a committee is formed, and for the life of the scheme, regular community meetings are held to discuss the operation and maintenance of the scheme. The level of community engagement and commitment towards operation and maintenance are cornerstones of the sustainability of the scheme (Blanco et al., 2008). Thus, it is possible to assume that a community's perceived value of the scheme can affect the operation and maintenance of the scheme. Furthermore, it can be hypothesised that the greater communities' livelihood benefits will result in better operation and maintenance and thus increase scheme sustainability.

The objectives of this study are to outline the most common livelihood improvements afforded by MHP schemes and to identify if a relationship exists between the communities' livelihood improvements and the sustainability of the scheme. The capability approach is used in this study to quantify the livelihood improvements that schemes bring to communities, and a method is suggested to understand how communities value such changes.

4.2 Methods

4.2.1 Schemes visited and interviews

To evaluate the social impact of MHP schemes on communities, 17 remote communities from Bolivia and the Philippines were studied during 2015 and 2016. These schemes represented a range of active and non-functioning schemes implemented by local developers in each country. Local developers were contacted to obtain key information on scheme and community characteristics. Schemes varied in years of operation, households serviced by MHP, regions, and power generation (Table 13). The education level of community members was of high school or lower. Subsistence agriculture was their main activity and all communities visited appeared to be around the poverty threshold (WorldBank, 2017).

Table 13. Synopsis of the micro-hydro schemes studied in Bolivia and the Philippines.

Scheme	Years Operatin	Households	Region	Power (kW)
Bol.1	7	25	Andean	6
Bol.2	2	14	Andean	8
Bol.3(nf)	8	80	Sub-Andean	100
Bol.4(nf)	14	30	Sub-Andean	16
Bol.5(nf)	12	40	Sub-Andean	8
Bol.6(nf)	6	120	Sub-Andean	38
Bol.7(nf)	11	180	Llanos	40
Bol.8	1	60	Sub-Andean	35
Bol.9	7	313	Sub-Andean	100
Phi.1	7	58	Cordillera	15
Phi.2	9	14	Cordillera	5
Phi.3	14	43	Cordillera	6
Phi.4	16	52	Cordillera	7
Phi.5(nf)	6	100	Negros Island	32
Phi.6(nf)	5	30	Negros Island	5
Phi.7	8	200	Negros Island	32
Phi.8	8	150	Negros Island	32

(nf) – MHP scheme not functioning

Interviews on scheme implementation and community livelihood were carried out during the site visits (Table 14). Participants had to be adults, residents of the community, and users of the electricity generated by the scheme. Interviews were held casually and individually (avoiding social desirability biasing). To facilitate the interview process and results analysis, questions were short, concise and of a yes/no nature.

Table 14. Study interviews description.

Interview	Countries	Number of interviewees	Gender
Scheme implementation	Bolivia	64	33 F; 31 M
Community livelihood	Bolivia and Philippines	93 (64 Bol. 29 Phil.)	48 F; 45 M

Scheme implementation interviews were carried out in the nine communities in Bolivia. Individual interviews provided qualitative information on the community's response and engagement during the phases prior, during, and post implementation of the scheme. Information was recorded on the social effects, barriers, issues and limitations of the implementation process of schemes.

Community livelihood interviews were carried out in 17 communities in Bolivia and the Philippines. The individual semi-structured interviews on 22 livelihood indicators (i.e., 22 questions) revealed which aspects of their livelihood had changed thanks to the arrival of the MHP scheme. The interview allowed for qualitative additional comments that helped understand the rationale behind the answers. The interviews also inquired on the 'overall well-being contribution' of electricity, by asking if the arrival of electricity had contributed to their general comfort, had freed up time, or had helped towards doing their chores more effortlessly. Interviewees were further asked to rate five basic aspects of their life: health and diet, safety, education, community engagement and leisure, and economy (named 'livelihood sub-set perceived importance' in this study).

4.2.2 The capability approach

The capability approach principle

This study used the capability approach (Robeyns, 2005) as a way to measure the livelihood changes that a MHP scheme brings to a community after its implementation. The livelihood of the community is defined as the combination of the individual well-being of the members of the community. Measuring well-being is a complex task, thus, this study has adopted the concept of well-being as the evaluation of the well-ness of the person's state of being, or, how much a person is succeeding in 'doing' or being' (Sen, 1993).

To explain the relationship between the arrival of a MHP scheme and the well-being of an individual, the logic path followed by the capability approach is explained and exemplified in Figure 7.

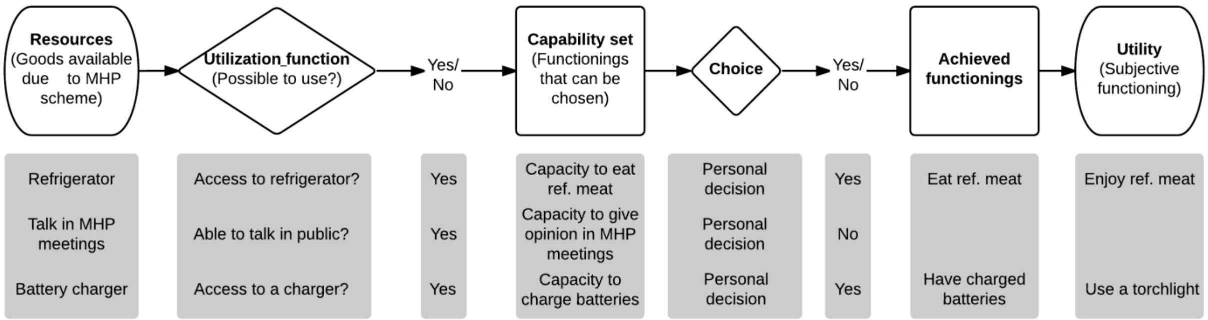


Figure 7. Capability approach relationships exemplified.

The arrival of electricity through MHP allows for numerous potential resources to be available to communities. The utilization function is the capacity of an individual to make use of a given resource. It is limited by both internal (physical and mental capabilities) and environmental (society rules, culture, climate, etc.) factors. A resource that can be used is then called a functioning. The capability set of an individual are the functionings that the individual has actual access to. The choice is the decision taken by the individual over the usage of its capability set, and it is entirely up to the individual. If a functioning is chosen, and hence achieved, a utility is realised.

To measure the communities' livelihood, this study quantifies the functionings that individuals have access to (capability set) and the achieved functionings. The bigger the capability set and the achieved functionings of the communities' individuals, the higher the community livelihood.

If the MHP scheme provides individuals with more functionings, and individuals extract more utilities out of achieved functionings, it is safe to assume that individuals can relate such new possibilities and personal achievements with the MHP scheme, thus increasing their appeal towards the scheme. To quantify an increase in the capability set and achieved functionings of the people of the community, this study used the semi-structured interview 'community livelihood'.

The 22 livelihood indicators of the 'community livelihood' interview represent functionings and achieved functionings given by the MHP (Figure 8). These account for some of the most common livelihood improvements associated with the installation and implementation of a MHP scheme.

The arrival of a MHP scheme can bring to a community a vast range of changes across multiple livelihood fields: education, health, agro-production, energy, safety, economy, telecommunications, social life, technology, etc. However, in this study we are concerned with the most basic capabilities, that is, those "basic things that are necessary for survival and to avoid or escape poverty" (Robeyns, 2005). To simplify result evaluation, the capabilities studied have been grouped in sub-sets of "crucially important capabilities" (Hausman, 1994). The selected sub-sets chosen in this study are those that reflect some of the most basic human necessary capabilities: health and diet, safety, education, community engagement and leisure, and economy.

4.3 Results and discussion

4.3.1 Scheme implementation response

The schemes visited in this study were implemented by local developers using a similar implementation process. The 'Scheme implementation' interviews in Bolivia revealed key information on the community's response:

i. Developers initiate community-scheme engagement by giving a series of workshops to the community, explaining the benefits of the technology, familiarizing the community with the physical principles of MHP generation, and preparing them for the construction and maintenance of the scheme. This initial community engagement is viewed by the developers as an important process to establish intensive community involvement, which is essential for the scheme operation and long term sustainability (Drinkwaard et al., 2010). During the preliminary workshops, 90% of the people said they had an active participation, and 93% said that they enjoyed such meetings. When asked if they enjoyed learning about the technology, 89% answered positively, and 85% said they'd like to learn more.

ii. When the construction process starts, the community is asked to participate with the acquisition of materials and construction of the civil works. 78% of the interviewed people in Bolivia participated in building the scheme, with 90% enjoying the process.

iii. A MHP village committee is formed, and community training continues, a process "necessary for the system to continue to run for years to come" (Kabalan et al., 2014a). After the construction of the scheme, operators are chosen to conduct regular maintenance. When major repairs to the civil works are needed, members of the community contribute to the repairs. 63% affirmed having participated with the repairs of the scheme during the life of the scheme.

The arrival of a MHP schemes brings a wide range of opportunities. It also generates in the community a sense of empowerment, offers an opportunity to work together, and fosters communal problem solving and decision making. These positive contributions are reflected by the high rates of active participation during the construction and maintenance of the scheme.

The 'Scheme implementation response' interviews were not conducted in the Philippines; however, the casual observations suggest that the two countries appeared to have a similar involvement in the MHP scheme implementation stage.

4.3.2 Community livelihood

The question on the 'overall well-being contribution' revealed that 68% of 93 interviewees responded that electricity contributed to general comfort, a fact frequently explained by the comfort brought by the improved lighting. Electricity was not reported as contributing to free time. Some reported that with improved businesses they worked extended hours, and some reported that they now spent too much time watching TV, hence the low positive responses (32%). Only 30% responded that electricity helped towards doing their chores more effortlessly, with only a few reporting that cooking and house cleaning duties could be done easier.

The percentage of positive responses to semi-structured household interview done in Bolivia and the Philippines for the 22 indicators of the 'Community livelihood' were varied (Figure 8). Difference in responses between genders and between countries was also observed for some indicators.

Health & Diet	Q1-F	Do you have access to better health facilities?	*
	Q2-AF	Do you have less health related issues?	
	Q3-F	Do you have access to refrigerated food?	*
	Q4-AF	Do you eat refrigerated food?	*
	Q5-F	Is the quality of your diet better?	
Safety	Q6-F	Do you have access to emergency services?	*
	Q7-AF	Have you ever used the emergency services?	*
	Q8-AF	Do you spend more time outside at night?	*
	Q9-AF	Have you had less home accidents?	
Education	Q10-F	Has your children's education improved?	
	Q11-F	Do you have more time to study at night?	
	Q12-AF	Do you study more hours at night?	
	Q13-AF	Have you participated in any new educational activity?	
Com. Engagement & Leisure	Q14-F	Do you have access to communal lit areas at night?	*
	Q15-AF	Do you spend time on such areas at night?	*
	Q16-F	Can you give your opinion in MHP communal meetings?	+
	Q17-AF	Do you give your opinion?	+
	Q18-F	Do you have more leisure time now?	*+
	Q19-AF	Do you have internet or a cell phone?	
Economy	Q20-AF	Has your home income increased thanks to the MHP?	
	Q21-AF	Do you save money on lighting?	
	Q22-AF	Do you save money on other energy needs?	*

+ difference in genders higher than 15%
* difference in countries higher than 15%

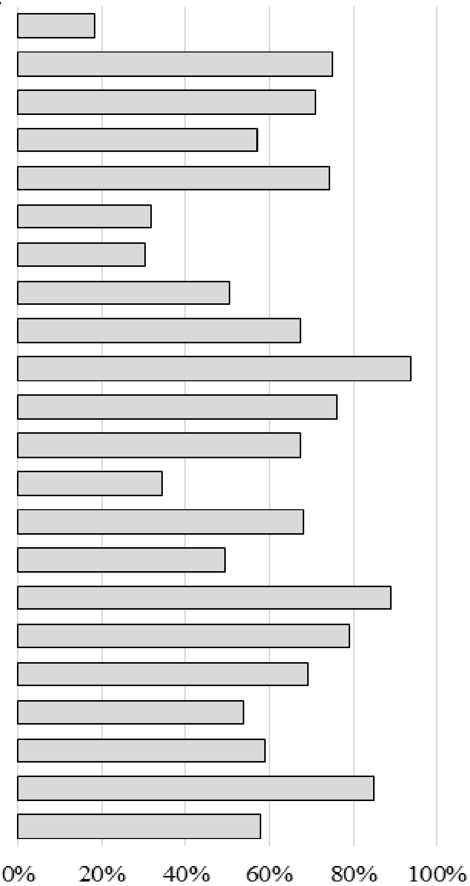


Figure 8. Percentage of positive responses for the semi-structured interview for 22 Community livelihood' indicators. An 'F' or 'AF' next to the question number indicates a functioning (F) or an achieved functioning (AF) type question.

HEALTH & DIET

Only three of the studied communities, all in Bolivia (27%), reported having an improved health post facility as a direct consequence of the MHP scheme. The people interviewed in those communities reported that they could now have refrigerated medicines and a place for outside doctors to come and do workshops on health practices, nursing, disease treatment and vaccinations. None of the other communities reported access to better health facilities, thus an overall low positive response (18%) (Figure 8, Q1), although the potential for improved health facilities is acknowledged.

The electrification of villages can bring numerous health and diet benefits. The most significant impact was the reduction of health issues (75%) (Q2). Traditional methods of generating light (i.e., candles and kerosene lamps) produce fumes that generate headaches, respiratory problems and eyesight loss. It also increases the probability of fire accidents, especially with children. Better lighting allows for better cleaning of the food and of the houses. Better lighting, also, makes stumbling less likely, a fact of special importance, as the most common source of injury reported was tripping due to low visibility, a recurrent and dangerous event for the elderly. Moreover, mending and cleaning of wounds is more precise and can be done comfortably during night-time, when farming duties are over. Communities from both countries also reported that with extended hours of light, chores could be distributed more easily during the day, resulting in a less stressful life. However, despite household power allowance limitations and running costs, some communities used incandescent and halogen lights, unaware of more efficient (but often more costly in the short term) modern lights (i.e., LED and CFL).

Communities from both countries often reported having enough power to run refrigerators (71%) (Q3). The majority of communities in Bolivia run refrigerators (84%). In the Philippines, communities showed less need for refrigerators (41%), as their diet seemed more vegetable based (lesser need for refrigerating meat or fish). Communities with access to refrigerators made good use of them (57%) (Q4). Bolivian communities had higher rates of refrigerated food consumption (67%) compared to the Philippines (34%) because they had more access to refrigeration. Refrigerated food allows for better food quality and quantity due to less spoilage. Significant increases in diet variety and quality were reported for both countries (74%) (Q5).

Better lighting makes food cleaning and cooking easier, a fact reported by most women, who are traditionally in charge of preparing meals. It also extends meal time and makes it more pleasant (i.e., better visualization of food), resulting in higher food consumption. Electricity, also, allows for ice making and for the use of blenders, especially convenient for two countries where fruit consumption is high.

The arrival of electricity, thus, brings to communities multiple health and diet improvements. Better lighting presents new ways to prepare and consume food, opportunities that communities make good use of. However, it also represents a sudden change to traditional eating habits. Elders in a few Bolivian communities pointed out that due to the cultural changes brought by television and the use of refrigerators, young people regularly consumed sugary fizzy drinks, resulting in apparent higher rates of overweight people and diabetes.

It is recommended that developers promote low energy use CFL or LED lights to improve indoor lighting quality which will allow for increased health and diet benefits (fewer accidents and more pleasant eating conditions at night). It is also recommended that developers promote additional subsequent benefits, such as the construction or improvement of health facilities.

SAFETY

Four Bolivian communities (44%), and one Philippine community (7%), saw the arrival of a phone or radio emergency service as a direct consequence of the MHP scheme (32%) (Q6). The telephone or radio are used in case of extraordinary needs, such as a doctor, arranging and emergency transport, or for important communication. Remote communities usually do not have a resident doctor and in case of emergencies a doctor has to be called in or the patient needs to be transported to the nearest health post. Emergency services were regularly used in Bolivian communities (44%), while in the Philippines was never used (0%), for an overall result of (30%) (Q7).

Street lighting has been reported to be a positive input towards safety during night-time, especially for women (González et al., 2009). However, this study did not reflect this phenomenon. Lack of light during night-time was not a security issue for women in these communities, a fact also reported in a study in Pakistan, where women explained that prevailing restrictions in society are the source of insecurity, and not darkness (Mueller et al., 2012).

On average, interviewees in both countries expressed spending more time outside (51%) (Q8) simply due to the comfort brought by light. The cold climate of some of the communities in Bolivia resulted in fewer people spending time outside at night (44%) compared to communities in the Philippines (66%) where the climate is warmer.

Interviewees also reported a reduction in home accidents (67%) (Q9), a fact often explained by the safety brought by electric lighting, as opposed to conventional and dangerous flame sources of light.

EDUCATION

Communities' reported that improved lighting at schools and households had a significant positive impact on children's education (94%) (Q10). Schools have extended teaching hours (especially in winter) and can now make use of new educational material, including projectors, DVD players, and computers. At home, extended light hours give children more flexibility to do their homework and read books.

The impact on the community adult's education, however, is complex. Despite extended night study time (76%) (Q11), multiple interviewees affirmed they'd rather watch television, claiming education was no longer possible for them, and that farming duties occupied most of their time. However, extended light hours and better light quality helped people read magazines, books, and the bible (67%) (Q12). Occasionally, schools organize adult activities and workshops making use of projectors, speakers, computers, etc. (34%) (Q13). However, these events are scarce and it was evident that communities were not fully aware of the educational possibilities that electricity can bring.

The arrival of TV offers a new source of entertainment, expands educational boundaries, and acts as a powerful source of news and miscellaneous information. Some communities reported TV greatly boosted language learning. Multiple studies have seen the arrival of TVs as a positive input, without arguing in detail the in-depth consequences (Barnett et al., 2000), (Gurung et al., 2011) (Bastakoti, 2006). However, this study has received mixed feedback by interviewees on the impact of TV in communities, and identifies a number of negative impacts. Communities that had extensively enjoyed television had experienced a clear loss of local culture and traditional values, manifested through alteration of clothing fashion, music styles, and social behaviours, a fact more evident with youth. It was reported that dinner times are often spent watching TV resulting in reduced social interaction. Television programs in developing countries also suffer the usual absence of educational material and do not lack abundant political indoctrination content. Television can, thus, expose communities to problems suffered globally that endanger communities’ identity, but on the other hand it has the potential to be a positive input towards communities’ education.

The arrival of a MHP scheme has positive and negative impacts into the education, cultural values and social dynamics of remote communities. It is recommended that developers provide workshops on the adequate uses of the newly available technology for educational purposes.

COMMUNITY ENGAGAMENT AND LEISURE

During night time, interviewees reported increased access to communal lit areas (68%) (Q14). In Bolivia, the lighting of communal areas was more recognized by developers (90%) than in the Philippines (21%). 42% (Q15) of interviewees made use of communal lit areas. In Bolivia, a 63% of the interviewees reported using the communal lit areas to socialize during night time, while only a 21% of the interviewees in the Philippines reported spending time in such areas.

MHP schemes generate new sources of community interaction. Committee meetings around the operation and maintenance of the scheme present new opportunities for socialization. Most communities have monthly open meetings where the majority of the members of the community can participate (89%) (Q16). However, less women claimed that they could give their opinion (80%) compared to men (98%). Women often argued that their husbands were in charge of such duties. Most interviewed community members highly regarded such opportunity, and took advantage of the meetings to express their thoughts (79%) (Q17). The vast majority of men actively gave their opinion (94%), while women often argued that they did not have enough knowledge on the scheme, nor felt confident enough to express their ideas (64%). Such difference represents the most significant utilization function difference between genders observed in this study. The majority of the committees were solely formed by men, and no woman was found in charge of the operation of the schemes. Interestingly, women are the primary users of the electricity yet men are the main decision-makers, a fact previously identified in other studies. A study in Nepal, a leading country in MHP development, concluded that "unless women's energy is accounted for and credited, alternative energy initiatives are likely to remain unsuccessful" (Mahat, 2004). Cultural dynamics in many developing countries leave women with fewer opportunities to receive education, hence reducing their capacity to actively participate in MHP decision making (Nussbaum, 2000, Gurung et al., 2010). Women's interest in the functioning of the scheme was highly variable, and it was not unusual to hear women claiming they had no interest in it. However, it remains unknown how much of the lesser appeal of women towards the technology of MHP is due to social conditioning. The impact of the meetings, however, seemed positive for both genders, creating a sense of empowerment and generating opportunities for the people to express their ideas.

Leisure time was increased significantly in both countries (69%) (Q18). People claimed chores could be done faster with better visibility, duties could be planned better through the day, and children required less attention. These factors were more important to women (78%), who spend more time at home with children, than to men (60%). For most men, who spend most of the day working on the fields, leisure only happens at evening time. Philippine communities seemed to have more free time (83%) compared to the Bolivian (63%), a fact already observed in question 15. Cell phones were now used by some members of the community (54%) (Q19) especially for those with relatives living outside of the community.

The overall impact on community engagement and leisure was positive; however, differences exist between genders and countries. Both countries reflected that women gained higher benefit from the reduction of drudgery resulting in higher leisure time, but did not benefit as much from the opportunities brought by the organization behind the operation and maintenance of the MHP scheme or the communal meetings. To increase women's feeling of belongingness, representation and participation towards the MHP scheme, it is recommended to apply affirmative action, requiring the participation of at least one female member in each MHP committee.

ECONOMY

Households reported an increase in home income (59%) (Q20) because businesses could be enhanced with new machinery (fridges, welders, sawmills, grain mills), opening hours of retail shops were often extend until midnight thanks to improved lighting, and home manufacturing businesses, such as knitting, could continue production during night-time. Moreover, several jobs were created for the operation and maintenance of the scheme and sometimes new businesses, such as enhanced agricultural production, were possible utilizing machinery such as rice hullers, corn mills, or sugar cane presses. The creation of these new productive uses of energy is of special importance, as it is the "most direct way of justifying a new scheme on economic grounds" (Paish, 2002).

Households highly benefited from the reduction of lighting cost (85%) (Q21), which varied from a half to a fifth of the original cost without MHP. Communities also expressed savings on other energy needs (58%) (Q22), such as diesel, gas, wood, or batteries. This was of special importance to the Philippines (79%), reporting greater savings due to less usage of batteries for torchlights, compared to Bolivia (48%).

A study in Bolivia found a reduction of 54% in household expenditures for energy services (González et al., 2009). The reduction in use of these products represents less products (i.e. batteries) being disposed inadequately, thereby avoiding pollution, and less exhaustion of local resources (i.e. firewood). Interviewed people emphasized that savings should also consider the elimination of the cost of time and fuel to acquire the previous energy sources, including light sources (kerosene, candles, resins, etc.), a fact especially important in very remote communities, where reaching supply areas can take days.

Electric energy brings multiple economic benefits to communities. Readily available electricity inside households causes a great reduction of cost of purchase and transport of other energy sources. With the arrival of the scheme, new businesses reliant on the operation of the MHP scheme are created, generating revenue, and increasing scheme sustainability.

Capability sets and achieved functionings

Interviewees from both countries saw a significant increase in their capability set (i.e. functionings that can be chosen), and achieved functionings. The overall average positive responses for the examined functionings was 66% ("F" in Figure 8). This study confirms that the arrival of a MHP scheme does bring new possibilities to communities, and that the possibilities brought can be effectively used by the people (i.e., positive utilization function). The overall average of positive responses for the examined achieved functionings was 59% ("AF" in Figure 8), which suggests that the new possibilities are positively valued by people and are utilized.

The overall average does not show significant differences between genders on functionings or achieved functionings. A difference, however, exists between the functionings brought to communities in the Philippines (54%) and to Bolivia (71%). Developers in the Philippines has a higher focus on the electrification of households. Such difference is explained by the lack of access in the Philippines to communal lit areas, emergency services and health facilities.

Livelihood sub-sets

The grouping of all indicators into the 5 sub-sets, reveals similarities across countries and genders. However, differences exist in the Health and Diet and Community Engagement and Leisure sub-sets between the two countries. (Figure 9).

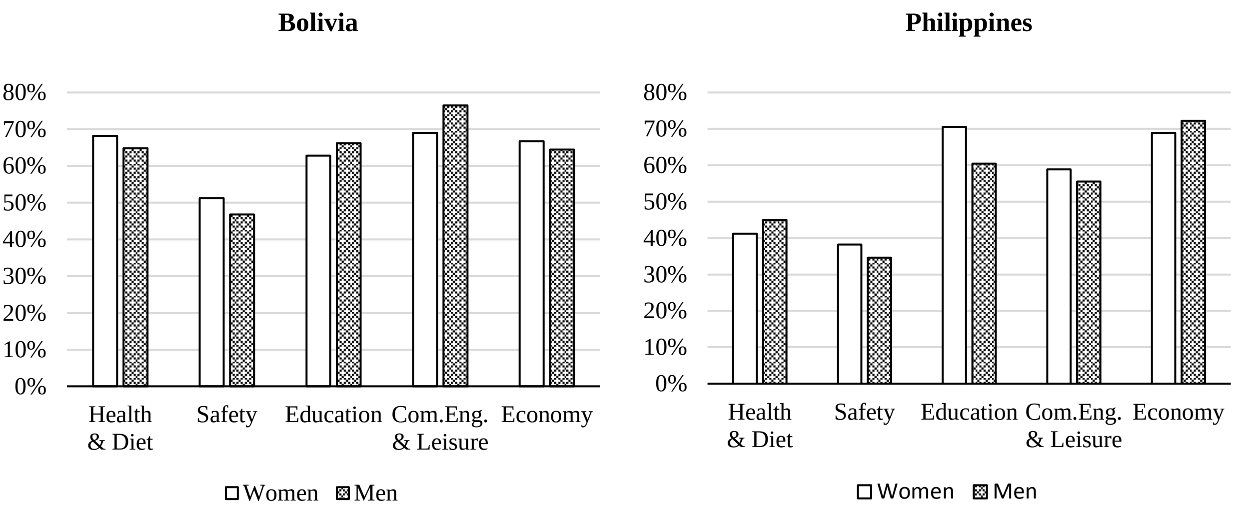


Figure 9. Percentage of positive answers grouped by sub-sets for Bolivia and the Philippines.

Bolivian communities had increased access to health facilities thanks to the construction of health posts. Moreover, Bolivian communities had a higher access to refrigerated food (84%) and consequently a higher consumption of such food (67%), whereas Philippine communities had low access (41%) and low consumption (34%).

The differences in the Community Engagement and Leisure sub-set are explained by the different use of communal lit areas. Only a 21% of the Philippine interviewees had access to lit area, compared to the 90% of Bolivian interviewees.

The results of the 22 indicators, when grouped by sub-sets, show that a MHP scheme brings to communities a range of benefits, especially, but not restricted to, education, community engagement and leisure and economy. The similarities between the two countries, despite existing cultural and geographical differences, suggest that other communities from other countries could experience similar benefits. The sub-sets considered within this study do not reflect significant differences between genders, suggesting that both genders benefit similarly from MHP schemes.

Interviewees from both countries were also asked to rate the five basic aspects of their life (i.e., the five sub-sets) by level of importance (being 1 low importance, 2 moderate importance, and 3 high importance) (Table 15).

Table 15. Overall results for the 'Livelihood sub-set perceived importance' and 'Livelihood sub-set total average'.

Livelihood sub-set perceived importance	**Score Scale [1 - 3] (St.dev.)**	**Score Scale [0 - 1]**	**Livelihood sub-set total average (Total average of Figure 9)**	**Score Scale [0 - 1]**
1st - Education	2.75 (0.49)	0.87	1st- Com. Eng. & Leisure	0.68
2nd- Health	2.73 (0.50)	0.86	2nd- Education	0.68
3rd- Economy	2.47 (0.66)	0.73	3rd- Economy	0.67
4th- Safety	2.46 (0.69)	0.73	4th- Health	0.59
5th- Com. Eng. & Leisure	2.16 (0.64)	0.58	5th- Safety	0.45

Communities rated each sub-set with moderate to high importance, a result that corroborates that the chosen sub-sets are important aspects of the people's livelihood. Education was rated first (Table 15, (0.87)), and was the second sub-set that received most benefits, thus, it is reasonable to think that communities highly value the contribution towards education. Safety, on the other hand, was rated 4th (0.73) and was the sub-set that received least benefits. Interestingly, both countries perceived community engagement and leisure as the least important sub-set (0.58), arguably the least basic sub-set. However, results reflect that community engagement and leisure received the most benefits, which exposes the fact that some of the benefits brought by the MHP might not be as important for communities. The health sub-set was perceived as highly important (0.86), however, results reflect that schemes do not always provide health benefits (0.59). Perhaps a better understanding of what communities really value would allow developers to better tailor the scheme implementation method to target crucial specific post implementation benefits, such the promotion of improved health posts.

When analysing these results by gender and country, no significant differences were found.

4.3.3 Scheme extended sustainability

This study hypothesized that the higher the perceived value of a MHP scheme, the higher the sustainability.

We assume in this study that using the communities' own criteria on the importance of the studied livelihood sub-sets is a valid method to estimate the real effect of each scheme on its community. Thus, to estimate the perceived value of a MHP scheme for a community, communities have received a score that is the result of the sum of their 'Livelihood sub-set' scores weighted according to their own score on 'Livelihood sub-set perceived importance', creating a 'Scheme perceived value' score.

To measure the sustainability, this study has adopted a simplistic approach and has used the age of the scheme as the reference value.

Results for the eight Philippine and nine Bolivian communities on the correlation between the 'Scheme perceived value' and scheme sustainability show similar and positive values (Figure 10).

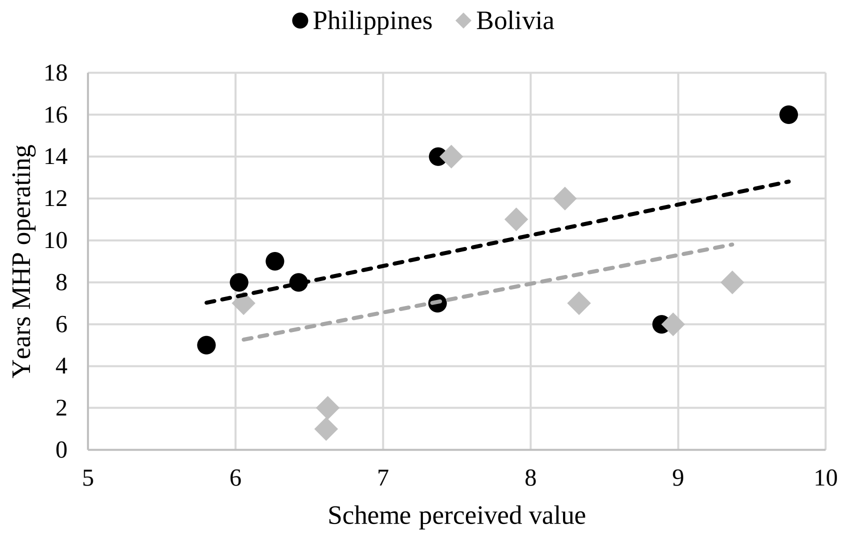


Figure 10. 'Scheme perceived value' and years of MHP operation for all studied communities.

The Pearson correlation coefficient values for Bolivia and the Philippines are 0.37 and 0.54 respectively. However, the significance of these correlation results is limited by the number of studied schemes. It is also necessary to remember that "correlation does not imply causation" (i.e., other unknown causal relations might exist).

The results are positive, and indicate that when communities value their scheme highly, it has a positive impact on the sustainability of scheme. These results, however, should be analysed carefully, and it is recommended that a study with a higher number of communities is performed to further verify the hypothesis.

4.3.4 Limitations

The indicators of this study have been classified by sub-sets to ease the evaluation of results. However, certain indicators have intrinsic relationships across sub-sets, such as safety and health. This study acknowledges that dependencies exist between indicators across sub-sets, however, claims that some of such dependencies are unavoidable, and that any livelihood study requires an open approach throughout the data evaluation process.

This study has focused on the most basic livelihood indicators that have also been mentioned in previous literature, and by doing so, has not studied other less basic capabilities that the MHP scheme might have increased, such as the use of computers, or playing sports during night time.

4.4 Conclusions

The results of this study have shown that the electrification of communities produces improvements in a wide range of livelihood indicators while providing higher levels of comfort to its beneficiaries.

The introduction of MHP schemes in communities resulted in a significant increase in new possibilities for individuals (i.e., capability set or functionings). People valued such possibilities and made good use of them. (i.e., achieved functionings).

Better lighting, arguably the most significant contribution, made daily duties easier and allowed communities to stay active after dusk, which resulted in a better distribution of chores and extended leisure times. Bolivia and the Philippines showed similar results for most of the 22 livelihood indicators studied. The few differences between the two countries resulted from the use of the electricity after the scheme implementation. Bolivian developers, for example, were influential in the upgrading of health posts and the lighting of communal areas.

Both genders benefited similarly from the arrival of MHP schemes. However, differences were observed in two aspects: men benefited more from the community engagement opportunities brought by the organization, operation and maintenance of the scheme, and women experienced a higher reduction of drudgery brought by the electrification of households.

The most important livelihood impacts produced by the arrival of a MHP were:

- Health problems produced by traditional light sources were highly reduced. Diet was enhanced by the use of refrigerators and better cooking methods.
- Safety was increased by the reduction of accidents due to the lack of visibility and use of flame light sources.
- Children's education was highly improved thanks to enhanced schooling and extended light hours. Night time reading hours were also increased for adults.
- The management, operation and maintenance of schemes increased community engagement and generated a sense of empowerment.
- The local generation of electricity cut energy costs and allowed for the improvement of existing businesses and the creation of new ones.

Communities reported increases in all the livelihood sub-set values analyzed. This study identified education as the livelihood improvement that communities benefited most from, and safety the least. Schemes that had perceived higher livelihood improvements thanks to the arrival of the scheme showed higher levels of sustainability, verifying the initial hypothesis of this study. However, the arrival of MHP schemes often represented an abrupt change for communities, resulting in negative diet alterations, TV misuse, cultural changes and community identity loss.

It is recommended that developing organizations adopt a pro-active approach towards preparing communities, not only to build, operate and maintain schemes, but also to maximize the post-implementation livelihood improvement opportunities identified in this study.

5. Micro-hydropower pre-feasibility assessment tool

5.1 Introduction

Remote communities in mountain ranges of developing countries often do not have access to the national electric grid. Micro-hydropower (MHP) schemes are thus often recognized as a cost-effective technology that can harvest the potential energy of rivers and generate electricity to meet the demands of those communities (Paish, 2002). MHP schemes have also been associated with community socio-economic advantages, positive environmental impacts, and increased community livelihood (Gurung et al., 2011; Pokharel et al., 2008; Mainali et al., 2013; Arnaiz et al., 2018).

Many isolated communities, however, are often unaware of MHP technology and cannot perform pre-feasibility assessments due to lack of know-how. In the context of developing countries, site identification and scheme implementation is typically done by local NGOs reliant on either government support or international aid. Generating pre-feasibility assessments is costly, as these require experts visiting the potentially remote community (Smith, 1994). The lack of local expertise in MHP pre-feasibility assessments and the need for expert site visits has limited MHP adoption in many developing countries.

In countries such as Bolivia, Cambodia and the Philippines, MHP technology is not widely known by communities and growth in MHP development since the 1990's has been limited. Site identification and pre-feasibility assessments mostly occur by personal references from developers or NGO's, a phenomena that might apply to other developing countries worldwide. As a result, developers operate in confined regions, leaving other areas with MHP potential unexplored.

On the other hand, in Nepal, the leading country in community owned MHP schemes with more than 1,152 schemes built since 1962 (Nepal Ministry of Finance, 2015), most communities are aware of MHP technology and can lodge a petition for a pre-feasibility assessment to a local governmental institution. However, the process can be slow, and still requires a team of experts to visit the community.

MHP is a site specific technology and its cost depends highly on the physical characteristics of the site (Mainali et al., 2013). The remoteness of many communities makes accurate pre-feasibility assessments a key factor affecting the project total cost (Mainali et al., 2013; Huang et al., 2014). To facilitate site identification, lower the cost of pre-feasibility assessments, increase the speed of scheme implementation, and allow communities to perform pre-feasibility assessments locally, there is a need for an easy to use pre-feasibility assessment tool that can be used by developers as well as villagers.

Developers have traditionally assessed the feasibility of MHP schemes by measuring key physical factors affecting the production of power (head and the river flow) and by assessing its economic feasibility (Smith, 1994). Key qualitative (and difficult to measure) variables such as social characteristics of the community or the environmental impact of the scheme are often disregarded (Kabalan et al., 2014). A holistic approach, however, seems necessary, as other factors such as the community's social attributes, or the environmental impact on the river ecosystem, have an impact on the likelihood of success of schemes. To this date, no holistic and easy to use pre-feasibility assessment method for the evaluation of MHP schemes has been published.

The objective of this research was thus to create an easy to use tool for pre-feasibility assessment of the likelihood of success of a potential MHP scheme in a remote community in a developing country. A multi-criteria decision method was used in this study to incorporate the key criteria that determine the likelihood of success of a community owned MHP scheme. Pre-feasibility assessment tools were created for each individual country as well, and the relative importance of the key criteria is discussed.

5.2 Methods and tool development

The MHP Pre-feasibility Assessment Tool (MHP-PAT) (Figure 11) was created to assess the likelihood of success of a potential MHP scheme in a remote community. The tool was validated by comparing the results of a multi-criteria decision method (MCDM) against the results of the scheme current success score (SCSS), which is a score based on field observations and interviews obtained through site visits to 35 schemes.

Four decision factors and 15 decision criteria were selected based on the knowledge gained throughout field visits and current literature. To determine the relative importance of the selected factors and criteria of the MCDM, these are weighted against each other. The decision alternatives (i.e., the characteristics of each one of the 35 schemes) are then selected and introduced in the model.

In each computational run, a different weighting for the decision factors and criteria is tested until all possible weighting combinations are tested. The combination that renders a best match (i.e., highest correlation coefficient) between the results of the MCDM and the results of the SCSS is selected as the best MCDM that explains the 35 schemes and the tool is considered validated (Figure 11). To evaluate how the two sets of data match, the correlation coefficient, the root mean square error (RMSE) and Nash-Sutcliffe efficiency coefficient are used.

This tool validation is thus an exercise in inverse problem solving, where a set of observed data (i.e., the SCSS) is used to find a solution that best explains a given data set.

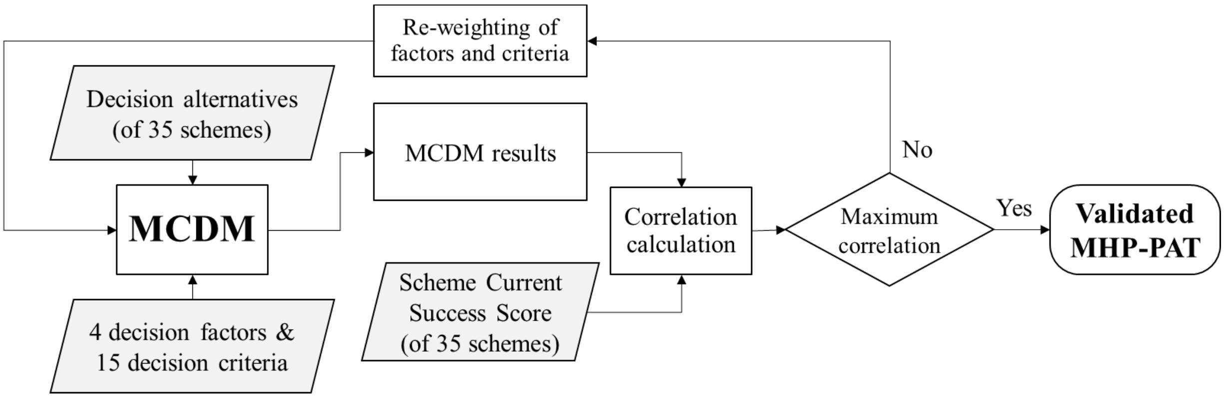


Figure 11. Validation of the MHP Pre-feasibility Assessment Tool.

5.2.1 Data acquisition

This study uses data gathered on 35 schemes across Nepal, Bolivia, Cambodia and the Philippines from 2015 to 2016 (Arnaiz et al., 2018). The information on each scheme was acquired during site visits and interviews with local developers, scheme operators and electricity beneficiaries. Success criteria scores of schemes from the communities' point of view were measured and a 'Current Scheme Success Score' (SCSS) was produced (Table 16). Success was measured as the degree to which a scheme accomplished its purpose of generating power in a sustainable way for the scheme and the environment while satisfying the needs of the community. The study gathered information on scheme current power generation and water availability, operation and maintenance state, environmental damage and community approval and allocated points according to the degree in which the success criteria was accomplished (i.e., the more points, the more successful) (Table 16).

Table 16. Success scores for different criteria and total success score for the Nepalese, Bolivian, Cambodian and Philippine schemes visited.

Scheme	Power (kW)	Power generation (0-8)	Operation & maintenance (0-4)	Environmental damage (0-2)	Community's approval (0-4)	Scheme Current Success Score (SCSS)
Nepal 1	86	8	2	1	4	**15**
Nepal 2	17	8	2	2	4	**16**
Nepal 3	16	8	2	2	4	**16**
Nepal 4	26	8	3	1	4	**16**
Nepal 5	10	8	3	0	3	**14**
Nepal 6	22	6	2	1	4	**13**
Nepal 7	15	6	2	0	2	**10**
Nepal 8	12	4	2	0	2	**8**
Nepal 9	24	8	2	2	2	**14**
Nepal 10	1	4	1	2	2	**9**
Bolivia 1	6	4	4	2	3	**13**
Bolivia 2	8	8	2	2	4	**16**

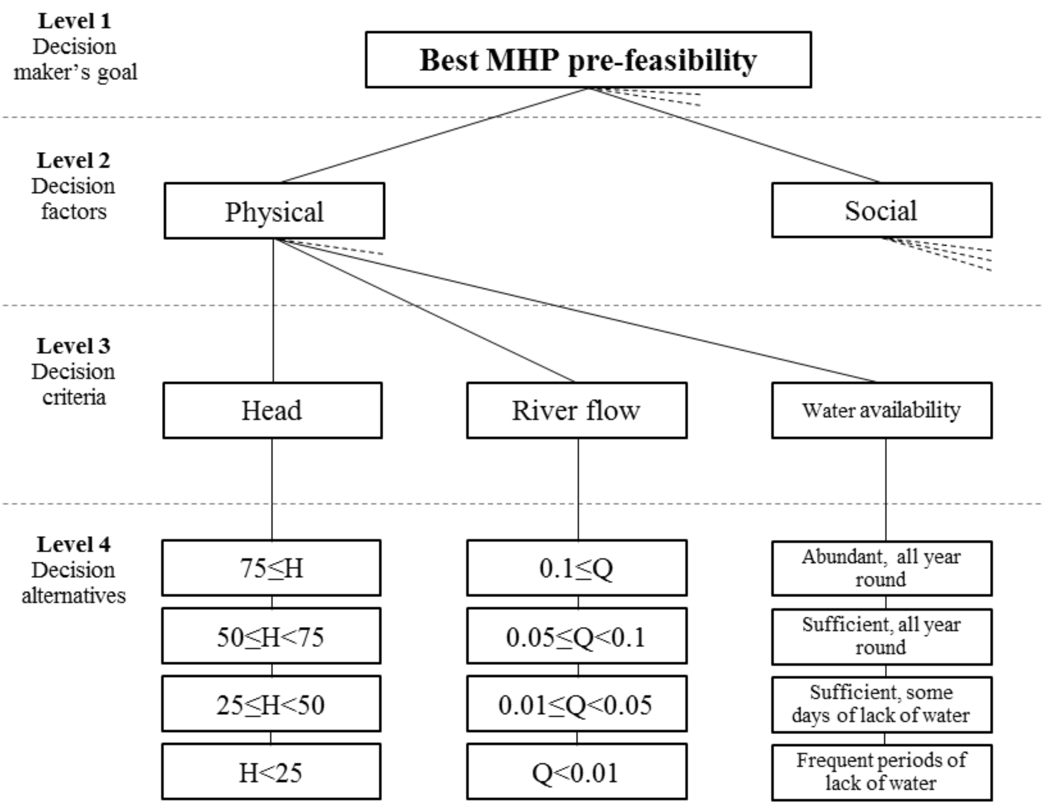
Bolivia 3	2	8	3	2	4	**17**
Bolivia 4(nf)	100	4	1	0	1	**6**
Bolivia 5(nf)	16	4	3	1	4	**12**
Bolivia 6(nf)	8	2	2	0	3	**7**
Bolivia 7(nf)	38	4	2	0	4	**10**
Bolivia 8(nf)	40	2	2	0	3	**7**
Bolivia 9	35	8	2	1	4	**15**
Bolivia 10	100	2	1	1	3	**7**
Cambodia 1(nf)	12	4	2	1	3	**10**
Cambodia 2	8	6	0	1	1	**8**
Cambodia 3	10	6	4	1	4	**15**
Cambodia 4	40	2	4	1	2	**9**
Cambodia 5	0.6	4	2	2	3	**11**
Cambodia 6	0.5	2	3	2	4	**11**
Cambodia 7	3	2	2	2	4	**10**
Philippines 1	15	6	1	1	2	**10**
Philippines 2	5	6	3	2	4	**15**
Philippines 3	6	8	1	0	4	**13**
Philippines 4	7	8	2	2	4	**16**
Philippines 5(nf)	34	2	2	2	1	**7**
Philippines 6(nf)	5	8	4	2	2	**16**
Philippines 7	28	8	2	2	3	**15**
Philippines 8	22	6	2	2	3	**13**

(nf) – Not functioning

5.2.2 Multi-criteria decision making

Multiple quantitative and qualitative variables affect the likelihood of success of MHP schemes. A multi-criteria decision method (MCDM) is thus necessary to create a tool that incorporates the key variables which affect the likelihood of success of schemes. For the tool to be used by developers and villagers, the tool should be suitable for most MHP sites and should be easy to understand and manipulate. Several MCDM methods were considered, such as ELECTRE (Roy, 1990), SMART (Edwards, 1977), PROMETHEE (Brans et al., 1985), or Analytic Network Process (Saaty, 2005). These, however, have been discarded for either not being able to include qualitative criteria, not being intuitive and easy to manipulate, having high levels of subjectivity, forcing relationships between criteria, or having criteria and decision alternatives that cannot be applied to a MHP pre-feasibility assessment. The analytic hierarchy process (AHP), on the other hand, is a suitable method that can incorporate quantitative and subjective qualitative data, is easy to use, understand and manipulate, and produces mathematic objective results (Bhushan et al., 2007).

The AHP helps identify the best solution of a complex problem according to the decision maker's goal. The method creates a model that is easy to understand and is intuitively structured, can integrate qualitative and quantitative variables and can be easily manipulated (Ishizaka et al., 2011). A hierarchical structure breaks down big concepts into small concepts through levels. Four levels were required for the construction of the MHP-PAT model (Figure 12).



H values are in meters. Q values are in m^3/s.

Figure 12. Partial representation of the hierarchy structure of the MHP-PAT.

5.2.3 Model development

To create the MHP-PAT model, four steps were used to explain the assumptions and design choices for the tool development.

i. Hierarchical division: for the MHP-PAT model to be easy to use and manipulate, and so that results can be interpreted, it needs to be divided into levels of criteria that comprise independent sub-criteria (i.e., the relationship between criteria of *k* level cannot be affected by the relationship between criteria of *k+1* level). In the construction of the AHP model, the number of levels depends on the complexity of the problem and on the degree of detail required to solve the problem (Zahedi, 1986). A compromise is necessary between the number of levels and the number of decision criteria per level. Field studies and interviews with experts revealed that the feasibility of MHP schemes depends on 4 decision factors (level 2: physical, social, environmental and economic). Key decision criteria (level 3) are then grouped under each decision factor. Decision alternatives (level 4) are then required under each decision criteria (level 3), completing the hierarchical model shown in Table 17.

Table 17. Levels of decision factors, criteria, and alternatives for the MHP Pre-feasibility Assessment Tool.

Level 2 (Decision factors)	Level 3 (Decision criteria)	Level 4 (Decision alternatives)
1. Physical	1.1 Head [m]	1.1.1 75≤H
		1.1.2 50≤H<75
		1.1.3 25≤H<50
		1.1.4 H<25
	1.2 River flow [l/s]	1.2.1 0.1≤Q
		1.2.2 0.05≤Q<0.1
		1.2.3 0.01≤Q<0.05
		1.2.4 Q<0.01
	1.3 Water availability	1.3.1 Abundant, all year round
		1.3.2 Sufficient, all year round
		1.3.3 Sufficient, some days of lack of water
		1.3.4 Frequent periods of lack of water
	1.4 Village-intake distance [m]	1.4.1 d≤250
		1.4.2 250≤d<500
		1.4.3 500≤d<750
		1.4.4 750<d
	1.5 Accessibility to area	1.5.1 Road access, under one hour walk
		1.5.2 Road access, multiple hours walk
		1.5.3 No road access, multiple hours walk
		1.5.4 No road access, one day or more of walk
	1.6 Terrain complexity	1.6.1 Very simple topography, very stable terrain
		1.6.2 Simple topography, stable terrain
		1.6.3 Complex topography, unstable terrain
		1.6.4 Very complex topography, very unstable terrain
2. Social	2.1 Community cohesion	2.1.1 Very united
		2.1.2 United
		2.1.3 Divided
		2.1.4 Very divided
	2.2 Ongoing communal projects	2.2.1 Multiple
		2.2.2 One
		2.2.3 None
	2.3 Presence of mechanics	2.3.1 Multiple
		2.3.2 One
		2.3.3 None
	2.4 People's involvement in civil works	2.4.1 Guaranteed
		2.4.2 Likely
		2.4.3 Unlikely
3. Environmental	3.1 River biodiversity	3.1.1 No biodiversity
		3.1.2 Low biodiversity
		3.1.3 High biodiversity
	3.2 Presence of diesel generators	3.2.1 Multiple
		3.2.2 One
		3.2.3 None
4. Economic	4.1 Financial support (NGO, loan, subsidy, etc.)	4.1.1 Likely
		4.1.2 Possible
		4.1.3 Unlikely
	4.2 Demand of electricity from a business	4.2.1 Likely
		4.2.2 Possible
		4.2.3 Unlikely
	4.3 Village economic contribution	4.3.1 Likely
		4.3.2 Possible
		4.3.3 Unlikely

To identify the key decision criteria (level 3) affecting the likelihood of success of schemes, this study adopted a learning-based analytical approach. The experience gained throughout the visits to the 35 communities during 2015 and 2016, interviews with academics, MHP users, and developers, as well as informal talks with community members, together with the study of the current literature, allowed for the identification of the most suitable criteria. The identification of the most common success and failure reasons in a study by Arnaiz et al. (2017) contributed to the selection of the decision criteria for the pre-feasibility tool.

Decision criteria were also selected on the basis of their measurability and simplicity, so that villagers from remote communities and developers can apply the tool. Albeit other variables exist that affect the likelihood of success of MHP schemes, these have not been selected for not being important enough, not being applicable to all schemes and communities, or being complicated to measure or understand.

The decision alternatives (level 4) are the options to choose from by the users of the tool, which should best describe the characteristics of the potential scheme at the given location. These have to be unambiguous and best represent most possible scenarios. A high number of alternatives can make selection difficult. For a more consolidated result, multiple users of the tool can average the decision alternative choices.

ii. Pair-wise comparison (PWC): to calculate the relative importance of the decision elements (factors, criteria, and alternatives), these have to be pair-wise compared. For the PWC this study uses Saaty's 9 point linear scale (Saaty, 1990) (Table 18).

Table 18. Saaty's linear pair-wise comparison (PWC) scale (Saaty, 2003).

Intensity of importance	Definition	Explanation
1	Equal importance	Two decision elements contribute equally to the objective.
3	Moderate importance	Experience and judgement favour one decision element over another.
5	Strong importance	Experience and judgement strongly favour one decision element over another.
7	Very strong importance	A decision elements is strongly favoured and its dominance demonstrated in practice.
9	Extreme importance	The evidence favouring one decision elements over another is of the highest possible order.

A reciprocal matrix *A* must then be generated for each decision criteria of k level where $A = \{w_{ij}\}$ is an $n \times n$ matrix where n is the number of level $k+1$ criteria, and the i,j' th entry w_{ij} is the relative importance of criteria *i* over *j*. Note that $w_{ij} = 1/ w_{ji}$ and the diagonal terms $w_{ii} = 1$. Thus this matrix contains all the PWCs over the *n* different criteria.

Table 19. Reciprocal matrix and PWC for the decision alternatives of decision criteria 1.1 Head.

Reciprocal matrix for Head (decision criteria 1.1)	H>75	50<H<75	25<H<50	H<25
75≤H	1.00	**3.00**	**5.00**	**7.00**
50≤H<75	0.33	1.00	**1.67**	**2.33**
25≤H<50	0.20	0.60	1.00	**1.40**
H<25	0.14	0.43	0.71	1.00

For example, the reciprocal matrix for "Head" (decision criteria 1.1) in Table 17 has a matrix of size n=4, where only 6 PWCs (in bold) are necessary to describe the whole matrix (Table 19). For the complete MHP-PAT model, 97 PWCs are necessary (Table 20).

Table 20. Distribution of PWC through the 4 levels of the MHP-PAT.

Matrix size (n)	Number of matrices in each AHP level	PWCs	Total PWCs
2	1 (Level 3)	1	1
3	9 (1 in Level 3, 8 in Level 4)	3	27
4	9 (1 in Level 2, 1 in level 3, 7 in Level 4)	6	54
6	1 (Level 3)	15	15
		TOTAL	**97**

Each PWC has 9 possibilities (1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9). Thus, the preliminary total number of possible combinations of PWCs (and MHP-PATs) is 9^{97}.

iii. Relative weights (RW): the RW of an element *i* of a reciprocal matrix represents the numerical ranking (or weight) of such element within its reciprocal matrix. RWs can be derived from reciprocal matrices, and represent the relative importance of such element towards the decision maker's goal.

Such numerical ranking of the criteria can be achieved through the concept of a priority vector. The preference matrix *A* defines a priority vector $\boldsymbol{x} = [x_1, x_2, ... x_n]$ where x_i is the relative weight of criteria *i*. It can be argued that (i) the priority vector should be scale independent, that is, any positive multiple of a priority vector is a priority vector and (ii) that any weighting of a priority vector $\boldsymbol{x}$ by the preferences in *A*, that is, $A\boldsymbol{x}$, is another priority vector. This means that a priority vector is an eigenvector of *A* (Eqn. 1),

$$Ax = \lambda x \quad (1)$$

λ in Eqn. 1 is an eigenvalue of the matrix *A*. Note that the reciprocal matrix is a positive matrix. The Perron-Frobenius theorem guarantees the existence of a largest positive eigenvalue

λ_{max} with a corresponding principal positive eigenvector (Pillai et al., 2005). This eigenvector is easily computed using the power method (Elsner et al., 1999), or Von Mises iteration, which is based on iterating *y* times an initial guess $\mathbf{x_0}$ (Eqn. 2).

$$x_{y+1} = \frac{A\,x_y}{||Ax_y||} \qquad (2)$$

Three iterations were found to be sufficient to generate precise eigenvectors (i.e., the fourth iteration showed changes on the 5th decimal position).

iv. Aggregated relative weights (ARW): the ARW of a decision alternative represents the total weight of the final MHP-PAT result. There are 15 ARWs (i.e., one ARW for each decision criteria), and the sum of all 15 ARWs represent the final score of the MHP-PAT. Each AWR is calculated by multiplying the relevant relative weights of level 2 times level 3 times level 4, as shown in Eqn. (3) for the example of the AWR for Head.

$$ARW_{(Head)} = RW_{(Physical)} \times RW_{(Head)} \times RW_{(75 \leq H)} \qquad (3)$$

Detailed information was recorded during the site visits on the physical characteristics of the scheme and the area, such as river flow or terrain quality, as well as information on the community social characteristics, scheme environmental impact and community economic characteristics. This information was used to select appropriate decision alternatives of each scheme, which allowed for the calculation of all ARWs.

The validation process determines the optimum set of RW. The tool is then ready to use. The user of the tool has to choose the decision alternative for each decision criteria (i.e., 15 choices) that best describes the characteristics of the potential scheme.

5.2.4 Computation

The MHP-PAT validation process requires a large number of PWCs, and the combination of these yield a very large number of possible solutions, as noted above. Thus, significant computation is necessary to consider all PWC possibilities.

However, the initial total number of possible combinations 9^{97} is not possible to compute. Multiple assumptions (A1, A2, and A3) have thus been made to reduce the number of computations. The assumptions adopted have been chosen on the basis of their capacity to speed up computation time without compromising the quality of the MHP-PAT results:

A1. If non-necessary pair-wise comparisons are not computed and are derived from necessary pair-wise comparisons, computation time will decrease significantly and matrices will be perfectly consistent (i.e., no consistency ratio calculation is necessary).

For each matrix, only the first row is necessary, as the next rows can be mathematically derived from row one:

If $w_{12} = 3$ and $w_{13} = 5$ then, $w_{23} = \frac{w_{13}}{w_{12}} = 1.67$

For a matrix size n, n-1 PWCs are thus necessary, reducing greatly the number of model inputs, and thus computation time.

A2. No decision criteria is ‘extremely more important’ (Table 18) than any other decision criteria in its reciprocal matrix.

The decision criteria chosen are considered of similar importance. Thus, the most extreme comparison values ‘extremely more important’ (i.e., 9 and 1/9) were discarded.

A3. If decision alternatives are selected and ordered to be moderately more important than the previous one, no pair-wise comparison is necessary for level 4, which reduces computation time. Thus, in Table 19:

- ‘75≤H’ is moderately more important than ‘50≤H<75’.
- ‘75≤H’ is strongly more important than ‘25≤H<50’.
- ‘75≤H’ is very strongly more important than ‘H<25’.

5.2.5 Model limitations

The MHP-PAT does not consider possible dependencies between elements of different matrices (i.e., ‘2.1 Community cohesion’ could affect ‘4.3 Village economic contribution’). The potential interdependence of decision criteria can lead to unpredicted results. Independency between decision criteria has been sought, although it is acknowledged that full independency is not possible. The assumption of linear independence has been previously identified as a limitation of the AHP (Ishizaka et al., 2011).

5.3 Results and discussion

In the following section we first discuss the results on key criteria importance obtained after validating the MHP-PAT for all four countries, named ‘global results’. We then discuss individual MHP-PATs (validated for each individual country) and compare the differences between key criteria importance with the global results. Finally, we discuss the sensitivity of the model.

5.3.1 MHP Pre-feasibility Assessment Tool global results

Validation computation

To select the PWC combination that produced MHP-PAT results that best match the results of the SCSS, the correlation coefficient, RMSE and Nash-Sutcliffe efficiency coefficient between the two sets of results was calculated for each iteration, and the optimum values were recorded. The three methods agreed on the best PWC solution values. The MHP-PAT model with assumptions A1, A2 and A3 resulted in a maximum correlation coefficient of 0.87, RMSE of 0.14 and Nash-Sutcliffe efficiency coefficient of 0.75, after iterating 7^{14} times (Table 21).

Table 21. Computation time and correlation for the MHP-PAT model.

	Full MHP-PAT	A1	A1+A2	A1+A2+A3
PWC Combinations	9^{97}	7^{97}	7^{51}	7^{14}
Computational time [min]	*	*	*	1350
Correlation coefficient	*	*	*	0.86807

*Preliminary computation runs with lower number of possibilities suggested an almost linear relationship between computation time and number of possibilities (i.e., ten times more combinations takes ten times more time to compute). Thus, all assumptions were necessary to perform calculations in a reasonable time on a PC.

The validation process (i.e., the selection of the best PWC combination) takes computing power and time. Once the model is validated, the application of the MHP-PAT, however, takes negligible time, and can be performed with minimum computing power.

MHP-PAT results

The results for the four countries for the MHP-PAT and the SCSS showed a strong correlation, however, small differences exist when comparing some individual countries. (Figure 13). To allow for a visual comparison, the set of MHP-PAT results and the SCSS were normalized by dividing each result by the average of results.

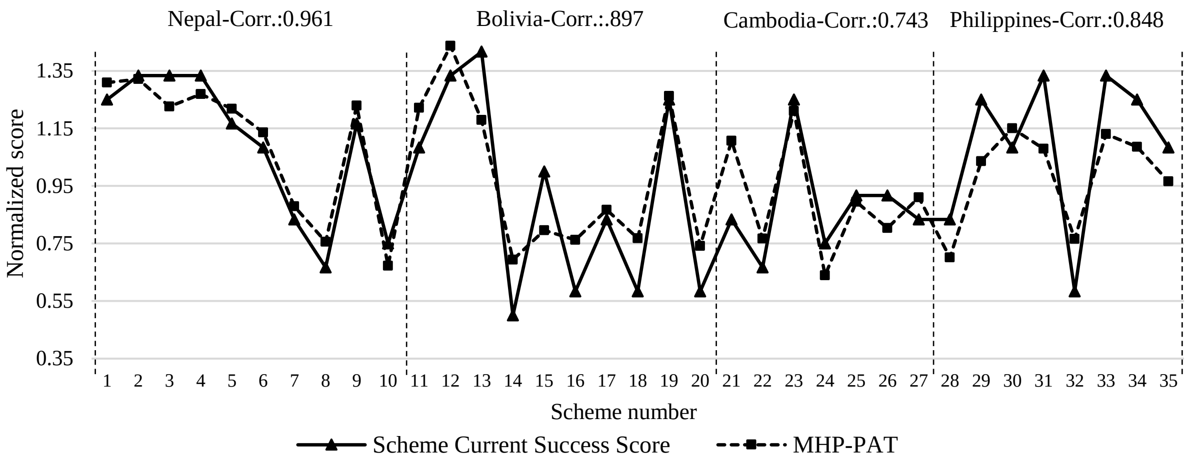


Figure 13. Normalized results for the MHP-PAT and the SCSS for the 35 schemes.

Nepal and Bolivia, with the highest number of schemes in the data set, show the highest correlation values (0.96 and 0.90 respectively), followed by the Philippines (0.85), and Cambodia (0.74), which had smaller numbers of schemes in the data set. Thus, the MHP-PAT is slightly more accurate for Nepal, followed by Bolivia, the Philippines and Cambodia.

Decision factors, criteria pair-wise comparisons (PWC) and relative weights (RW)

The first row of the reciprocal matrices show the validated combination of key PWC values of the factors of level 2 and the criteria of level 3 (Table 22). Results for all PWCs of the reciprocal matrices can be derived by following the calculations shown previously in *2.4 Computation – A1*.

Table 22. Results for the key pair-wise comparison (PWC) values and relative weights (RW) for the MHP-PAT.

Level 2	1. Physical	2. Social	3. Environmental	4. Economic		
1. Physical	1* (0.31) [#]	1 (0.31)	5 (0.06)	1 (0.31)		
Level 3	1.1 Head	1.2 River flow	1.3 Water availability	1.4 Village-intake distance	1.5 Accessibility to area	1.6 Terrain quality
1.1 Head	1 (0.07)	1 (0.07)	1/7 (0.46)	1 (0.07)	7 (0.01)	1/5 (0.33)
Level 3	2.1 Community cohesion	2.2 Ongoing communal projects	2.3 Presence of mechanics	2.4 People's involvement in civil works		
2.1 Community cohesion	1 (0.7)	7 (0.1)	7 (0.1)	7 (0.1)		
Level 3	3.1 River biodiversity	3.2 Presence of diesel generators				
3.1 River biodiversity	1 (0.88)	7 (0.13)				
Level 3	4.1 Financial support	4.2 Demand of power from industry	4.3 Village economic contribution			
4.1 Financial support	1 (0.6)	3 (0.2)	3 (0.2)			

* PWC comparison values follow Table 18 criteria.
[#] RWs are shown in parenthesis.

The results show that the feasibility of MHP schemes depends equally on the physical, social and economic factors, which are 'strongly more important' (Table 18) than the environmental factor (Table 22).

A survey ('four factor survey') of 12 MHP experts was conducted in Nepal in 2016 to estimate the degree of importance (from 1 to 5: none, minor, moderate, significant, great) of the physical, social, environmental and economic factors affecting the feasibility of MHP schemes. The 'four factor survey' results match closely the results of the MHP-PAT model (Table 23).

Table 23. Comparison of the results of the four factor survey against the PWC and relative weights.

Level 2	'Four factor survey' score	Rounded score	Physical factor's PWC values	Relative weights
Physical	3.75	4	---	0.31
Social	3.92	4	1 : Equal	0.31
Environmental	2.25	2	5: Strongly more important	0.06
Economic	3.83	4	1 : Equal	0.31

Physical factor

The results show water availability as the most important decision criteria, closely followed by terrain quality (Table 22). Accessibility was considered the least important factor.

Water availability is viewed as very important because the lack of water during the dry season results in insufficient or no power for MHP dependent communities and local businesses (retail shops, restaurants, vendors, etc.) (Murni et al., 2013). In developing countries, the lack of economic resources does not allow for detailed hydrologic studies (Smith, 1994) which often results in downtime periods from a few weeks to a few months. Downtimes are negatively seen by communities and is especially problematic for local production business (i.e., grain mills, carpentries, rice hullers, welders, etc.). Reliability is thus viewed which such high regard that multiple communities reported preferring the more expensive national grid (when available) just on the basis of its greater reliability.

Terrain quality is also considered important because communities in mountainous regions (Nepal, Bolivia, and Philippines) were often challenged by landslides that damaged parts of the scheme during the wet season.

The ease of access to the communities was initially regarded as a potentially important variable that could affect the transport costs for the construction and maintenance of MHP schemes. However, the results of the MHP-PAT suggest that perhaps communities are well adapted to travel long distances and it is not a barrier to supply replacement parts and technical support for the maintenance of the scheme.

Social factor

The results show community cohesion as the most important criteria within the social factors (Table 22). Ongoing communal projects, presence of mechanics and people's involvement in the civil works, followed and are all of equal importance.

During the implementation of the scheme, a MHP village committee is formed to hold regular meetings to discuss the operation and maintenance of the scheme, electricity allocation, social disputes, tariff collection and guarantee the continuous functioning of the scheme (Khennas et al., 2000). United communities with a strong committee seemed more capable of overcoming technical drawbacks and intervene in social disputes. The results of the MHP-PAT suggest that the community's cohesion is fundamental for the success of schemes, and that the other criteria are of much lower importance.

Environmental factor

The results show river biodiversity as very 'strongly more important' (Table 18) than the presence of diesel generators (Table 22).

Communities that had households running diesel generators appreciated the MHP scheme due to the reduction of noise and generator associated running costs, the time and transport cost to acquire the fuel, and the cost of the fuel. However, generators were only run by a few households. The reduction of the river biodiversity due to the reduction of river flow, however, affects the totality of communities that fish for subsistence, hence the higher importance.

Economic factor

The results show financial support as 'moderately more important' (Table 18) than the demand of power from an industry and the village economic contribution capacity (Table 22).

Maintenance and running costs of schemes are high, as these suffer failures regularly (Arnaiz et al., 2018). The capacity of the community to contribute economically to the maintenance of schemes without the help of external funding is key in ensuring the resilience of the scheme (Kabalan et al., 2014). The demand from industries, also known as 'productive end-uses', is also a well-known factor behind MHP schemes' economic sustainability, as these create revenue and look after the functioning of the scheme (Paish, 2002; Smith, 1994). MHP schemes' capital cost is high (Kirk, 1999), and without external financial support, communities are often unable to provide the necessary funds for the construction of the scheme.

Thus all decision criteria are of similar importance, however, securing the initial capital cost through financial support is the most important criteria.

MHP-PAT results interpretation

The results from the MHP-PAT can only be interpreted in a relative scale from 0 to 1 (i.e., against each other). To interpret these results, a Decision Making Scale (DMS) with five equal intervals (quintiles) has been adopted (Table 24). The intervals of the DMS have been chosen so that the results of the MHP-PAT match the results of the SCSS.

The user first introduces the decision alternatives for the studied scheme, then a recommendation on the feasibility of the evaluated scheme is produced by the tool according to the DMS (Table 24).

Table 24. Decision Making Scale for the MHP-PAT.

MHP-PAT Result	Recommendation
<0.27	Unlikely feasibility
[0.27,0.34)	Compromised feasibility
[0.34,0.4)	Possible feasibility
[0.4,0.46)	Likely feasibility
≥0.46	Very likely feasibility

ARWs decision criteria scores per country

To evaluate the differences in decision criteria scores between countries, the average ARWs scores for each criteria were classified by country. Average country ARWs scores were compared to global (four countries) ARWs, and decision criteria scores above and below 50% have been noted (Table 25).

Table 25. Differences in average ARWs scores between individual countries and the global average ARWs scores.

Country	Decision criteria	Score Diff.	Decision criteria	Score Diff.
Nepal	*Nil*		1.1 Head 1.5 Accessibility to area 3.2 Presence of diesel generators	-51% -60% -84%
Bolivia	1.1 Head	+69%	1.2 River flow	-50%
Cambodia	1.4 Village-intake distance 1.5 Accessibility to area 1.6 Terrain quality 4.3 Village economic contribution	+110% +68% +115% +50%	1.1 Head 2.3 Presence of mechanics 2.4 People's involv. in civil works 4.1 Financial support	-94% -63% -66% -92%
Philippines	1.1 Head 3.2 Presence of diesel generators	+60% +61%	1.6 Terrain quality	-63%

An example is used to help interpret results in Table 25: the head in Bolivia being +69% implies that the head values of Bolivian schemes (i.e., the level 4 decision alternatives) are larger compared to the average of the four countries.

Nepal

Three decision criteria had low scores: head, accessibility and presence of diesel generators.

Schemes in Nepal had low head values and bad area accessibility. Perhaps the high experience in scheme implementation has allowed for the successful implementation of schemes in very remote villages with low head values. None of the communities visited had diesel generators, thus, the change to a non-polluting, sound free and more economic technology (i.e., MHP) could not be a rationale for villagers to welcome the implementation of the MHP technology.

Bolivia

The decision criteria head had high scores, and the river flow low scores.

Six of the ten Bolivian schemes were located in very steep mountains in sub-tropical regions. Small streams located in the jungle at high altitudes were used as the water intake, thus the high performance on head and low performance on the water flow. Using precise flow measurements methods, or selecting adequately the water source, is thus of especial importance in Bolivia.

Cambodia

Four decision criteria had high scores: village-intake distance, accessibility to area, terrain quality, village economic contribution; and four decision criteria had low scores: head, presence of mechanics, people's involvement in civil works and financial support.

The high number of score differences can be explained by the lower number of schemes introduced in the model (seven) for Cambodia. Cambodian schemes were significantly different to those in Nepal, Bolivia and the Philippines. Schemes were built very close to villages and in nearly flat areas with good underground water sources. Six schemes were built with the economic contribution of small community groups or individuals, without any external financial support. Communities did not form a MHP committee, nor had trained operators.

Good available water resources exist nearby communities, thus, Cambodia presents good opportunities for MHP development that have not yet been capitalized by any national or international organization.

Philippines

Decision criteria head and presence of diesel generators had high scores, and terrain quality had a low score.

Schemes were typically built on steep rainforest mountains subject to severe monsoon rains and typhoon weather events, thus, schemes had high heads and were often built on steep rainforest mountains prone to landslides and subject to severe monsoon rains and typhoon weather events. Communities often had small diesel generators that would run during night time for lighting and during celebrations for music.

Prioritizing the quality of the terrain is thus key for the success of MHP schemes in the Philippines.

5.3.2 MHP-PAT results per country

To understand the decision factors and criteria differences between countries and to create MHP-PATs that better adapt to each country needs, the MHP-PAT model was validated for each individual country by only running computations with each country's schemes and by comparing the results with the country-specific SCSS results. New PWC optimal values for each country were found (Table 26).

Table 26. Results of the key PWC values and relative weights for the country-specific MHP-PATs (N-Nepal; B-Bolivia; C-Cambodia; P-Philippines).

Level 2	1. Physical	2. Social	3. Environmental	4. Economic		
N- 1. Physical	1 (0.43)	1 (0.43)	7 (0.06)	5 (0.09)		
B- 1. Physical	1 (0.39)	3 (0.13)	5 (0.08)	1 (0.39)		
C- 1. Physical	1 (0.06)	1/5 (0.31)	1/3 (0.19)	1/7 (0.44)		
P- 1. Physical	1 (0.37)	1 (0.37)	3 (0.13)	3 (0.13)		
Level 3	1.1 Head	1.2 River flow	1.3 Water availability	1.4 Village-intake distance	1.5 Accessibility to area	1.6 Terrain quality
N- 1.1 Head	1 (0.34)	3 (0.11)	1 (0.34)	3 (0.11)	7 (0.05)	7 (0.05)
B- 1.1 Head	1 (0.07)	1/5 (0.37)	7 (0.01)	7 (0.01)	7 (0.01)	1/7 (0.52)
C- 1.1 Head	1 (0.06)	7 (0.01)	7 (0.01)	7 (0.01)	1/7 (0.45)	1/7 (0.45)
P- 1.1 Head	1 (0.06)	1/7 (0.40)	3 (0.02)	1/5 (0.29)	1 (0.06)	1/3 (0.17)
Level 3	2.1 Community cohesion	2.2 Ongoing communal projects	2.3 Presence of mechanics	2.4 People's involvement in civil works		
N- 2.1 Community cohesion	1 (0.3)	3 (0.1)	1 (0.3)	1 (0.3)		
B- 2.1 Community cohesion	1 (0.11)	7 (0.02)	1 (0.11)	1/7 (0.77)		
C- 2.1 Community cohesion	1 (0.44)	7 (0.06)	1 (0.44)	7 (0.06)		
P- 2.1 Community cohesion	1 (0.12)	7 (0.02)	7 (0.02)	1/7 (0.84)		
Level 3	3.1 River biodiversity	3.2 Presence of diesel generators				
N- 3.1 River biodiversity	1 (0.13)	1/7 (0.88)				
B- 3.1 River biodiversity	1 (0.88)	7 (0.13)				
C- 3.1 River biodiversity	1 (0.88)	7 (0.13)				
P- 3.1 River biodiversity	1 (0.13)	1/7 (0.88)				
Level 3	4.1 Financial support	4.2 Demand of power from industry	4.3 Village economic contribution			
N- 4.1 Financial support	1 (0.11)	1/3 (0.33)	1/5 (0.56)			
B- 4.1 Financial support	1 (0.65)	3 (0.22)	5 (0.13)			
C- 4.1 Financial support	1 (0.65)	3 (0.22)	5 (0.13)			
P- 4.1 Financial support	1 (0.12)	7 (0.02)	1/7 (0.86)			

* PWC comparison values follow Table 18 criteria.
[#] RWs are shown in parenthesis.

The average aggregated relative weights (ARW) scores of each decision criteria for each country-specific MHP-PAT was measured and compared to the global MHP-PAT (Table 27).

Table 27. Differences in average ARWs scores between country-specific MHP-PATs and global MHP-PAT.

Global MHP-PAT contribution and per country MHP-PAT contribution of the decision criteria

	Global	**Nepal**	Diff.	**Bolivia**	Diff.	**Camb.**	Diff.	**Phil.**	Diff.
1.1 Head	1.5%	7.0%	5.5%	3.0%	1.5%	0.1%	-1.4%	2.6%	1.1%
1.2 River flow	2.0%	6.4%	4.4%	8.9%	7.0%	0.1%	-1.9%	13.1%	**11.1%**
1.3 Water Availability	10.6%	13.9%	3.3%	0.2%	**-10.4%**	0.1%	**-10.6%**	0.6%	**-10.0%**
1.4 Village-intake distance	1.5%	3.4%	1.9%	0.2%	-1.3%	0.1%	-1.4%	8.0%	6.5%
1.5 Accessibility to area	0.3%	1.3%	1.0%	0.5%	0.2%	5.1%	4.8%	2.0%	1.7%
1.6 Terrain quality	9.1%	2.3%	-6.9%	12.3%	3.2%	5.1%	-4.0%	3.6%	-5.5%
2.1 Community cohesion	20.9%	14.6%	-6.3%	1.1%	**-19.8%**	18.7%	-2.2%	4.4%	**-16.5%**
2.2 Ongoing communal projects	3.1%	5.6%	2.5%	0.2%	-2.9%	1.8%	-1.3%	0.7%	-2.4%
2.3 Presence of mechanics	3.6%	15.1%	**11.5%**	2.0%	-1.5%	10.9%	7.4%	0.9%	-2.7%
2.4 People's involv. civ. works	3.5%	18.5%	**15.0%**	13.7%	**10.1%**	1.4%	-2.1%	35.3%	**31.7%**
3.1 River biodiversity	6.3%	0.8%	-5.6%	7.2%	0.9%	25.3%	**19.0%**	2.4%	-3.9%
3.2 Presence of diesel gen.	0.6%	2.0%	1.4%	0.8%	0.3%	2.0%	1.4%	11.9%	**11.3%**
4.1 Financial support	25.2%	1.6%	**-23.6%**	38.2%	**13.0%**	13.8%	**-11.4%**	3.1%	**-22.1%**
4.2 Demand from industry	6.7%	3.9%	-2.9%	8.5%	1.7%	8.8%	2.1%	0.3%	-6.4%
4.3 Village economic contr.	5.0%	3.8%	-1.2%	3.1%	-2.0%	6.8%	1.7%	11.2%	6.1%

Correlations values for the country-specific MHP-PATs were: Nepal 0.99, Bolivia 0.95, Cambodia 0.95 and the Philippines 0.99. However, results in this section need to be analyzed carefully, as such small number of schemes cannot be highly representative of all country MHP schemes. In Cambodia, however, where the total number of MHP schemes in the country is suspected to be very low (i.e., under 20), the results of the MHP-PAT validated with 7 of those schemes could be considered highly representative.

Nepal

The physical and social factors are the most important factors and the economic, followed by the environmental, the least important.

Terrain quality and accessibility are the least important criteria, perhaps due to the better quality of the soil and better construction techniques. Nepal is the only country (of the four studied) that uses a standardized flow measurement method (salt dilution method and national geodatabase) to estimate flows in the dry season, which explains why issues with water availability are not as important as in the global MHP-PAT.

The presence of mechanics in the community and involvement of the community in the civil works are the decision criteria that have a higher contribution towards the final results. In a country where most communities are settled in similar physical conditions and with similar economic opportunities, the social characteristics of a community are perhaps what can make a higher impact towards the success of a scheme.

Nine of the ten schemes had financial support, thus, the MHP-PAT does not identify such decision criteria as influential in the success of schemes (i.e., cannot compare with schemes without financial support) and gives higher importance to the demand from industry and village economic contribution.

Bolivia

The physical and the economic factors are the most important, followed by the social and the environmental.

The terrain quality stands out as the most important physical decision criteria. Most scheme failures in Bolivia are related to the damage to the civil works due to strong weather events (Arnaiz et al., 2018). Water availability is of less importance, suggesting that seasonal variations are not severe enough to cause scheme downtimes due to lack of water.

Bolivian developers often found communities to be skeptical when explained that ‘electricity could be made out of water’. These, in turn, sometimes opposed participating in the civil works. The MHP-PAT shows the people’s involvement with the civil works as a more significant decision criteria.

Results for Bolivia further show the importance of securing financial support for the construction of schemes. The preliminary stages of the implementation of a scheme (i.e., financial support and people’s involvement in the civil works) appear to be key for the success of schemes.

Cambodia

The results on decision factors’ importance show a distinctive difference with the global MHP-PAT. The economic factor is the most important, followed by the social, the environmental, and lastly, the physical.

MHP is a technology that has been associated with mountain ranges. Interestingly, in Cambodia, where schemes are built in nearly flat areas, schemes seem to have overall good physical characteristics. The good levels of all year round underground water might explain the decreased water availability decision criteria importance.

No operation and maintenance workshops are given in Cambodia. Thus, the presence of mechanics in the community is of great importance.

The high importance of the river biodiversity (25.3%) is explained by the conflict with the water use: this is often extracted from ponds where multiple species exists that the community depends on (i.e. fish, crustaceans, etc.). It is recommended that future developers take into consideration such water resource conflict.

Philippines

The results for the decision factors show the physical and the social as the most important factors, closely followed by the environmental and economic factors, of similar importance.

Results show that the river flow has a clear prevalence over the water availability, suggesting that in the Philippines variations in seasonal flows are not as severe. The schemes visited in the Philippines were often located in very dense rainforest areas, thus the higher importance of accessibility to the area and the village-intake distance.

As in Bolivia, results do not show a very strong correlation between scheme success and the community's cohesion level, suggesting that, like in Bolivia, communities are already very united and operate communally. The people's involvement in the civil works, however, appears to be of great importance, suggesting that a high involvement with the scheme might be key to the success of schemes.

The Philippines was the country with higher diesel generators occurrences. The households that were used to the advantages of electricity (thanks to the diesel generators), pushed strongly towards the installation and maintenance of the MHP schemes, thus contributing to the success of schemes.

All communities had financial support, thus the low economic decision criteria contribution.

5.3.3 Sensitivity analysis

A sensitivity analysis was done to understand impact of decision alternative choices on the overall MHP-PAT result of a scheme. Four decision criteria were chosen to represent the average MHP-PAT result variation based on changing a decision alternative (Table 28).

Table 28. Score variation due to decision alternative change.

Decision criteria	Score contribution to the global MHP-PAT	Score variation due to decision alternative change
4.1 Financial support	25.18%	12.52%
1.3 Water Availability	10.64%	7.87%
4.3 Village economic contribution	5.04%	3.75%
2.4 People's involvement in civil works	3.52%	1.90%

The average impact on the final MHP-PAT result of changing a decision alternative is 4.2%.

Sensitivity was also evaluated to understand how much a variation on the SCSS would affect the MHP-PAT model. For a change in PWC values to occur, an average variation of 1.5 points in one scheme of the SCSS is necessary.

5.4 Conclusions

The MHP-PAT effectively integrates the key qualitative and quantitative variables required for a MHP pre-feasibility assessment. Reasonable assumptions were made to increase computational efficiency. The MHP-PAT was validated with a criteria pair-wise comparison combination that results in a strong correlation (0.87) between the results of the MHP-PAT and the scheme current success score for the 35 schemes analysed.

The model performed well and the results of the pair-wise comparison of level 2 (i.e. physical, social, environmental and economic) matched the opinion of MHP experts interviewed in Nepal. The MHP-PAT was optimized based on pair-wise comparison values that are in accordance with the findings gained throughout the site visits, user interviews and conversations with local experts and developers. The MHP-PAT has highlighted the importance of some decision criteria also described in recent literature, such as the water availability, terrain quality or the community cohesion.

The tool validation process classified the four factors (i.e., physical, social, environmental and economic) and decision criteria by their relative degree of importance. The following are the main findings from validating and applying the MHP-PAT:

- The physical, social and economic factors are of same importance, whereas the environmental factor is ‘strongly less important’.
- Water availability and terrain quality are the most important physical decision criteria.
- Community cohesion is ‘very strongly more important’ than ongoing communal projects, the presence of mechanics, or the communities’ involvement in the civil works.
- The river biodiversity is ‘strongly more important’ than the presence of diesel generators.
- All economic decision criteria are important, but financial support is ‘moderately more important’ than the demand form an industry and the village economic contribution.

The global MHP-PAT adapts adequately to the four studied countries, however, country-specific MHP-PATs were created with different pair-wise comparison values to better adapt to each country. Country-specific MHP-PATs can thus be easily created to better adapt to country specific needs. The results explain the 35 schemes analyzed very well, however, for greater representativeness, it is recommended that this tool is re-validated with a larger set of schemes.

This tool can allow remote communities to perform pre-feasibility assessments by making a simple selection of the key alternatives. The use of the tool in conjunction with developing organizations can improve MHP site identification. The use of the tool can also reduce pre-feasibility assessment associated costs and facilitate the scheme implementation process.

To implement the tool, decision alternatives can be introduced into a desktop application, an online data entry system, or a phone app. The decision making scale (DMS) effectively classifies the results of the MHP-PAT and makes possible a recommendation on the likelihood of success of a scheme. While generating a pre-feasibility assessment, the tool can record key information regarding a potential MHP scheme site. With the widespread use of the tool, such key information can facilitate the creation of national databases on MHP scheme region suitability.

6. Conclusions and recommendations

6.1 Research conclusions

This study used existing literature and the data gathered throughout visits to 35 communities with MHP schemes from Nepal, Bolivia, Cambodia and the Philippines, to evaluate the problems that MHP technology suffers, to understand how the implementation of schemes affect communities' livelihood, and to create a MHP pre-feasibility assessment tool. Extensive data was collected on each scheme and community during the site visits through observations and semi-structured interviews with experts, local developers and scheme users. Preliminary observations revealed that MHP technology faces multiple challenges: design and construction of schemes are done under severe economic limitations, communities' lack the capacity to operate and maintain schemes, and pre-feasibility assessments are costly and can lead to inaccurate site identification. Such challenges often result in poor scheme performance and lifespan due to inadequate construction techniques, insufficient water flow estimations, deficient community management techniques and overall poor operation and maintenance.

To understand the reasons behind the schemes poor performance and sustainability, success and failure reasons for the 35 schemes were recorded. To evaluate the current level of success of all schemes and allow a cross-country comparison, a framework was created to generate a scheme current success score. The main conclusions were:

- The reasons behind schemes failure are diverse, but often interrelated. The main cause leading to scheme failure is inadequate maintenance due to: deficient scheme operation and maintenance by operators and communities; inefficient scheme management by village committees; and low electricity tariffs leading to insufficient funds for repairs and replacements. Other important reasons leading to schemes ceasing operations that are not maintenance related are: the destruction of key scheme parts due to a severe weather events (i.e., landslides destroying canals, penstocks, or powerhouses, or flush floods destroying intake structures); the unexpected failure of expensive electric equipment (i.e., the ELC group); extended downtimes during dry season due to lack of water; or the arrival of the national grid, preferred for its reliability despite its higher cost. These reasons resulted in overall failure rates of 0.47 critical failures per year in the schemes studied.
- A gap exists between the capabilities of rural isolated communities and the capabilities required to operate and maintain successfully a MHP scheme. The workshops given by local developers on energy use and operation and maintenance during the implementation schemes are an effective, yet often insufficient, way of mitigating such problem. The government training

programs and subsidy system in Nepal are an effective way to help MHP schemes operate more successfully and for longer.

- Key factors for the long-term success of schemes were found to be: realistic river flow measurements of at least one year prior construction; at least two well-trained and well-paid operators; a realistic monthly tariff that allows not only for normal operation and maintenance duties, but also for the repair of unexpected scheme failures; a strong community support with a well-organized long lasting committee; and the external ongoing support from developers, governments, or the private sector.

To understand the livelihood impact that the implementation of a MHP scheme has on communities, the capability approach was used to evaluate 22 livelihood indicators grouped in 5 aspects: health, safety, community engagement and leisure, education and economy. Interviews were made to 93 electricity users from 17 communities from Bolivia and the Philippines. The main conclusions were:

- Improved d replaced was the most significant contribution to the five livelihood aspects studied, making daily duties easier and providing general comfort. Education and community engagement and leisure were the livelihood aspects communities benefited most from. Children’s education was enhanced due to improved school and home lighting. The scheme management through the village committee increased communities’ engagement and generated a sense of empowerment. Household economy increased due to the reduction of energy associated costs and the improvement of existing businesses or the creation of new ones. Health was increased thanks to the reduction of health problems associated with traditional light sources (kerosene) and better diet (through refrigeration). Lastly, safety was moderately increased thanks to the reduction of accidents produced by a lack of visibility at night or the use of flame light sources.
- Both countries benefitted very similarly from the livelihood improvements brought by the implementation of MHP schemes, however, Bolivian developers better fostered the post-scheme implementation improvement of health posts and provided lighting for communal areas used for socialization. Differences between genders were minimal, however, men took better advantage of the community engagement opportunities brought by the management of the scheme, and women benefited most from the reduction of drudgery.
- A correlation coefficient of 0.45 was found between the livelihood improvements brought by the implementation of MHP schemes and the lifespan of schemes.
- Several negative livelihood impacts were identified, such as negative diet alterations, TV misuse and community cultural identity loss.

The multi-criteria decision method analytic hierarchy process was used to design the MHP Pre-feasibility Assessment Tool. The MHP-PAT integrated the key qualitative and quantitative criteria that affect the likelihood of success of MHP schemes and classified them by their degree of importance. The main conclusion were:

- The results of the MHP-PAT and the results of SCSS have a strong correlation coefficient of 0.87, which indicates the model performs well. The tool can be easily understood and manipulated for other countries.
- Based on the data collected from the 35 schemes studied, the tool gave equal importance to the physical, social and economic factors, which are significantly more important than the environmental factor. Such results are in accordance with the opinion of the experts interviewed in Nepal. The most important criteria are the water availability, terrain quality, the community cohesion and securing financial support. The performance of each country in each individual criteria was measured, and over-performance and under-performance criteria was identified.
- Specific MHP-PATs models were created for each country. Significant variations in the importance of the criteria were highlighted. The MHP-PAT for Cambodia showed major differences to the global MHP-PAT. Results for Cambodia, a country seemingly less adequate for MHP due to its lack of steep mountain ranges, showed that the physical factor is significantly less important. Cambodia provides an example of successful MHP with low-head schemes thanks to good underground water resources (springs).
- With the help of a desktop application, an online data entry system or a phone app, the tool can record key information on scheme and community characteristics and generate a recommendation on the likelihood of success of a scheme at a given location, thus facilitating site identification, and allowing for the creation of national databases on MHP scheme region suitability.

This research contributed to understand why MHP schemes have limited sustainability by analysing the most common failure and success reasons. The creation of a holistic framework that measures the current level of success of schemes from the communities' point of view allowed for a cross-country comparison of scheme success scores. The detailed analysis of 22 livelihood indicators through the capability approach helped understand some of the livelihood changes that MHP schemes bring to communities, which livelihood aspects communities benefit most from, and how communities value such changes. The creation of the MHP-Pre-feasibility Assessment Tool can allow developers and communities generate a recommendation on the likelihood of success of a scheme for given location. Overall, the detailed study of 35 MHP schemes and communities across four countries helped advance the state of knowledge of community owned micro-hydropower in developing countries.

6.2 Recommendations and further research

This study created a tool to predict the likelihood of success of a MHP scheme. However, for the tool to be used, it needs to be programmed for a platform that can be easily used by community members and developers, such as a cell phone app, a desktop application, or an online data entry system. The tool needs to have a friendly and intuitive interface, provide minor explanations for each decision alternative so that these can be chosen easily. After the tool is programmed, it is recommended that the tool is tested in the field by the relevant local developers. It is recommended that maps of the most adequate regions for MHP development (i.e., best MHP-PAT results) are produced by local developers. The tool can also be applied to multiple countries to highlight country differences.

This study has evaluated the state of success of multiple schemes from Nepal, Bolivia, Cambodia and the Philippines. Many schemes in these four countries, however, remain unevaluated, and their current state of operation is unknown, a situation that applies to other countries as well. It is thus recommended that the success framework is applied more extensively by local developers in collaboration with local governments, and that national databases on the success level of existing schemes are created. The framework proposed in this study can be modified to include country specific characteristics.

The implementation of a MHP scheme has a big impact on the livelihood of communities. However, livelihood impacts are not properly understood by local developers and schemes are not implemented with consideration of such impacts. To maximize community livelihood improvements, and in turn extend scheme sustainability, it is recommended that developers foster post-implementation opportunities such as upgraded health facilities, efficient home and communal lighting, or improved education opportunities. It is recommended as well that developers perform community livelihood studies to better adapt to country specific needs. However, research is necessary to understand how local developing organizations can identify and maximize livelihood improvements. Research is also necessary into livelihood indicators that have not been explored in this study, such as the use of computers or playing sports during night time.

Current site identification and pre-feasibility assessment methods are costly and inefficient. The MHP-PAT was developed to be used (and manipulated if required) by developers and communities to easily create pre-feasibility assessments. However, the tool was validated with the data from only 35 schemes from four countries. It is thus recommended that the tool is revalidated with a larger sample of schemes and countries.

The current methods used to implement MHP schemes do not allow developers to be actively involved (i.e., provide economic and technical support) with a scheme after its implementation.

Without the technical and economic ongoing support of developing organizations, the sustainability of schemes is highly compromised. It is thus recommended that MHP project fund allocation considers the ongoing technical support for the lifespan of the scheme.

Like many other engineering solutions for developing countries, effective technology transfer is an important issue for community owned MHP schemes. Research is thus needed on optimal methods to transfer effectively the knowledge required to operate and maintain schemes successfully.

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ANNEX A – Interviews in Nepal

During the field trip to Nepal local MHP developers and experts were contacted as well as members of the Turbine Testing Lab (Kathmandu University). Many informal conversation revealed key information on MHP design, construction and operation and maintenance in Nepal. To record key information on MHP as well as information on current scheme success levels, multiple interviews were done:

- **MHP feasibility intervenient factors**: done to 12 experts and the 10 community representatives of the schemes visited, the interview aimed at identifying the importance of five intervenient factors in the feasibility of MHP schemes: physical, social, environmental, economic and political.
- **Report of Success:** done to the 10 owners of the 10 visited schemes, the interview aim at understanding the satisfaction of the community, operational status of the scheme, environmental damage, and economic and politic difficulties.
- **Expert interview:** done to 9 experts in MHP, the interview aimed at identifying the social and economic strengths weaknesses of MHP as well as the current threats and the technology suffer nowadays in Nepal.

MICRO-HYDROPOWER INTERVENIENT FACTORS

The aim of this survey is to acquire the pair-wise comparison criteria required to help develop the Micro-Hydropower Pre-feasibility Assessment Tool (MH-PAT), a tool that will help remote communities from undeveloped countries to assess the likelihood of success of a potential micro-hydroelectric scheme in their location.

Site location: **Date:**

Scheme construction date:

Projected power output:

This survey intends to compare five main intervenient factors to determine their importance towards the likelihood of success of a micro-hydroelectric scheme:

1. **Physical:** water flow, head, distance to the water source, and general geo-physical characteristics.
2. **Social:** attributes of the society, such as the organizational capacity, coordination, education, overall cohesion and demographic characteristics.
3. **Environmental:** effects on the river ecosystem, construction and maintenance ecological impact, consequences by changing to a renewable source of energy.
4. **Economic:** financing possibilities, community welfare, energy cost analysis, payback times and subsidizing opportunities.
5. **Political:** laws regarding the creation of the scheme, electricity tariffs, possibility to connect to the national grid and sell back electricity.

Express the importance of each one of the factors on the success of the micro-hydroelectric scheme by marking one of the options:

Factor	Great importance	Significant importance	Moderate importance	Minor importance	No importance
Physical	❑	❑	❑	❑	❑
Social	❑	❑	❑	❑	❑
Environmental	❑	❑	❑	❑	❑
Economic	❑	❑	❑	❑	❑
Political	❑	❑	❑	❑	❑

Are there any other significant factors that have influenced the likelihood of success of your micro-hydro scheme/s:

Results for the Micro-hydropower intervenient factors

This survey was done to both MHP experts and owners or community representatives. Figure A1 shows average results for the importance given by experts and owners where 1= "No importance" and 5 = "Great importance".

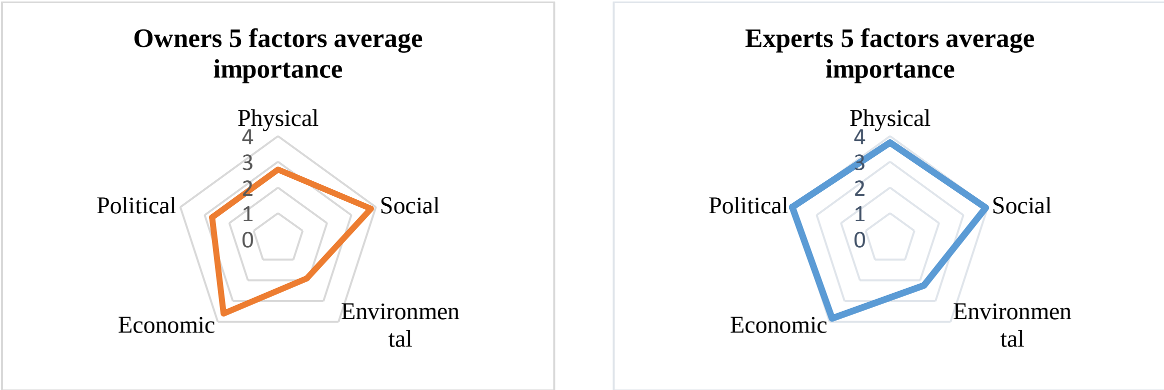


Figure A1. Average importance of the 5 intervenient factors for owners and experts.

- The answers from owners and experts show strong similarities. Thus, results suggest experts know what is important for communities and owners.
- The environmental factor is regarded as the least important factor, with average of "Minor importance".
- The Social and Economic factors are regarded as equally important with "Significant importance" (4) for both samples.
- The physical and political factors are regarded as less important by owners. Such factors are only considered when planning the construction of the scheme, thus the greater importance seen by experts.

REPORT OF SUCCESS

The aim of this survey is to collect the information required to evaluate the state of a micro-hydroelectric system to help develop the Micro-Hydropower Pre-Feasibility Assessment Tool (MHP-PAT), a tool that will help remote communities from undeveloped countries to assess the likelihood of success of a potential micro-hydroelectric scheme in their location.

Site location: **Date:**

Scheme construction date:

Projected power output:

In case of a negative or partial answer, further explanation might be requested.

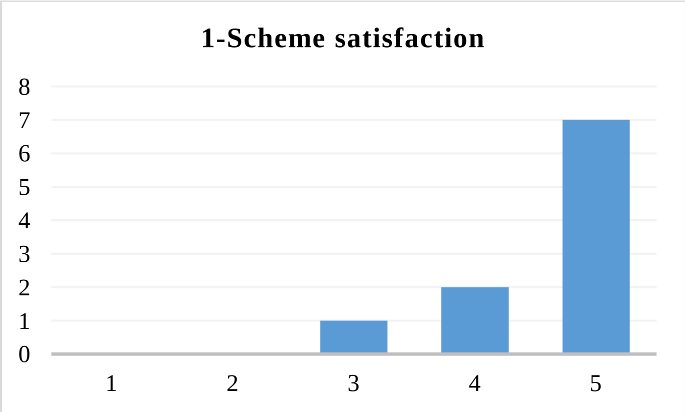
1. Using a scale from 1 – 5, meaning 1 very unsuccessful and 5 meaning very successful, how would you rank your micro-hydro scheme? Ranking ---------

2. Is the scheme functioning?		Yes ❑	No ❑
3. Has power been generated as expected?	Fully ❑	Partially ❑	No ❑
4. Has the intake water flow been sufficient to generate the expected power?	Always ❑	Sometimes ❑	Never ❑
5. Are the electricity users satisfied with the scheme?	Yes ❑	Some ❑	No ❑
6. Who does the maintenance of the scheme?	--		
7. Has scheduled maintenance been done as required?	Fully done ❑	Partially done ❑	Not done ❑
8. Has the scheme needed repairs or replacements?	Major repairs ❑	Minor repairs ❑	No repairs ❑
9. Has there been any unexpected damage to the quality and biodiversity of the water of the river?	Very affected ❑	Slightly affected ❑	Not affected ❑
10. Has there been any unexpected damage to the surrounding environment?	Major damage ❑	Minor damage ❑	No ❑
11. Have the users been able to pay for the electricity?	Most ❑	Some ❑	A few ❑
12. Was there any legal barriers to implement the project?		Yes ❑	No ❑

Results for the Report of Success

This section will show the results obtained from the interviews done to each one of the 10 schemes studied.

Questions 1 and 2



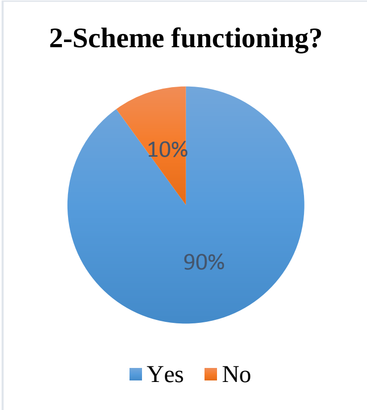
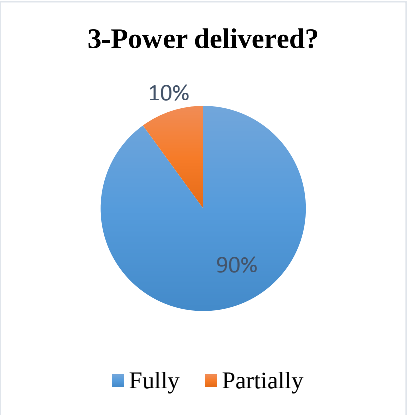
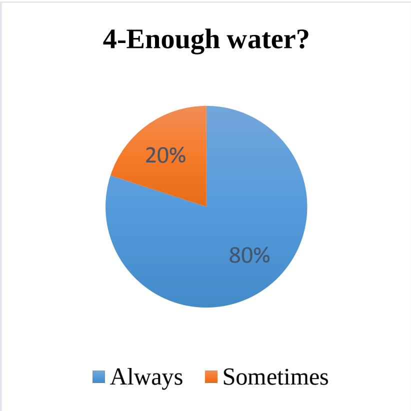


Figure A2. Results for questions 1 and 2 of the Report of Success.

The degree of satisfaction is very high. Interestingly, the non-functioning scheme scored a 5 in the level of satisfaction, as the scheme stopped functioning due to a flood that destroyed the intake.

Questions 3, 4 and 5





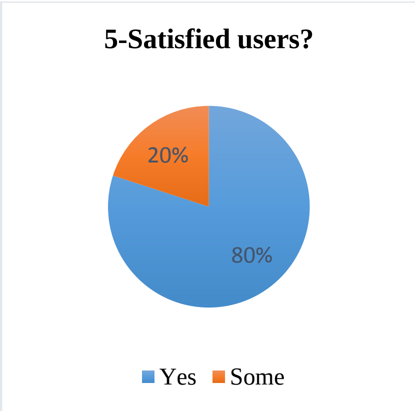
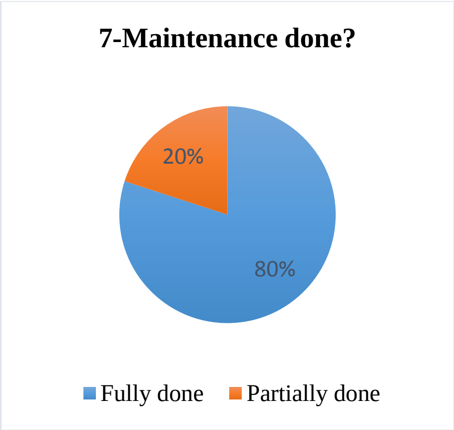


Figure A3. Results for questions 3, 4 and 5 of the Report of Success.

For power to be produced, water is necessary. Accordingly, both charts show similar results.

Most of the users showed a clear satisfaction. Users showing dissatisfaction were often users with a social problem, or in a geographical (i.e., far away from the scheme) or economic disadvantageous situation.

Questions 7 and 8



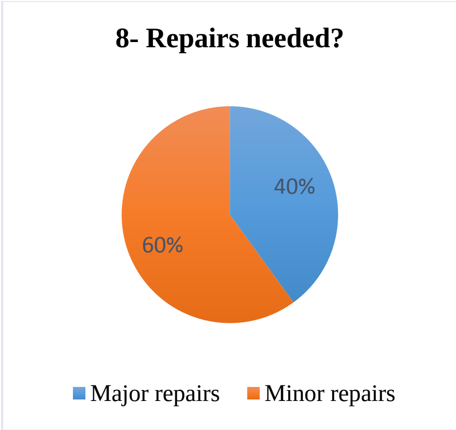
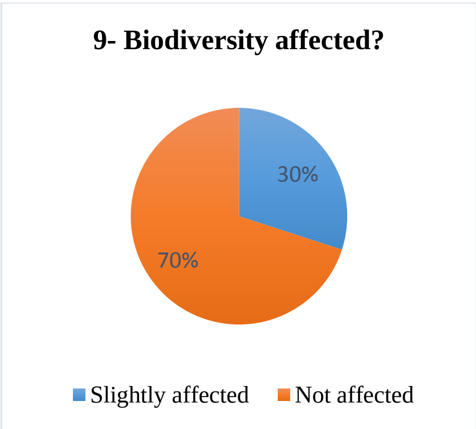


Figure A4. Results for questions 7 and 8 of the Report of Success.

Results show all schemes needed repairs. In the powerhouse, repairs ranged from minor electrical devices (mainly from the ELC) and mechanical replacements such as bearings, shafts or belts, to major failures in the generator, turbine, or pipework. On the civil works, most repairs were on the headrace due to landslides, intake fractures due to high river flows (i.e., heavy debris in flash-floods).

Maintenance sometimes was not done adequately. Schemes seemed to have the economic means to repair most setbacks, but often lacked the expertise to do so, or were not logistically ready. Schemes were always maintained by trained and paid operators from the village. Most schemes had two operators that would alternate between during day and night.

Questions 9 and 10



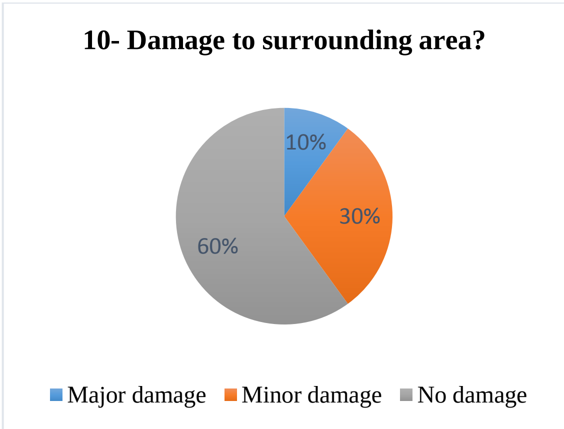


Figure A5. Results for questions 9 and 10 of the Report of Success.

Most schemes did no damage to the surrounding environment. Rivers either contained no fish, or the extraction of water was insufficient to damage fish populations. A complete study of the river biodiversity, however, was not possible. No investigation towards other biodiversity apart from fish is undergone by local authorities or communities.

Most of the damage caused to the surrounding environment was caused by water leaks, often as a consequence of a landslide, pipe burst, or headwork failure. Communities, however, repaired such scheme failures easily.

Questions 11 and 12

Question 11: users seemed to always pay the established tariff. The social structure seemed to not allow someone to delay payments. If a household had no money to pay, it would not be allowed to be connected.

Question 12: all interviewees pointed out that no legal barriers were found. For a scheme to be constructed, it needs to be approved by the government authority AEPC.

Expert interview sheet

Name: **Date:**

Organization:

Related experience:

1- Is MHP a known technology by Nepalese population?

☐

2- Do Nepalese want higher levels of electrification/access to power?

☐

3- Is the electrification of remote communities a positive input towards a better livelihood?

☐

4- Which is the main reason for the failure or malfunction of MHP schemes?

Technical	☐	Maintenance	☐	Economic	☐	Social	☐	Other	☐

5- In case of being able to choose, would Nepalese people prefer MHP or national grid?

MH	☐	NEA	☐

6- Why NEA doesn't want to buy generation under 100kW?

Technical difficulties	☐	Economically not	☐	Political reasons	☐	Other	☐

7- If small producers (down to 1kW) could sell electricity to the NEA:

7.1 Would creation of MHP be boosted? ☐

7.2 Would MHP be more sustainable? ☐

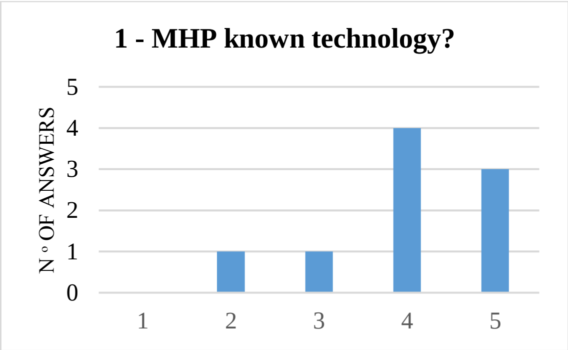
8- If the private sector was more involved after the creation of schemes, would schemes be more sustainable?

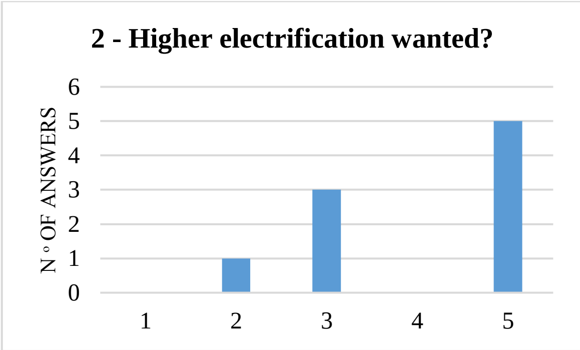
☐

Results for the Experts interview

Results show answers from the experts interview done to 9 people that either constructed, designed, or were professionally involved with MHP schemes. Graphics are answered with a score from 1 to 5, meaning 1very low (or negative), and 5 very high (or positive).

Questions 1 and 2

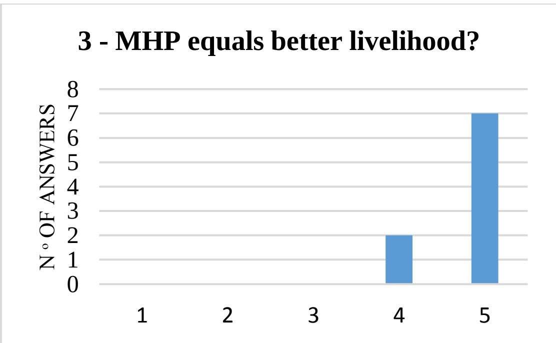




Question 1 shows a high level of awareness. The awareness of a society on an engineering solution can help the widespread and implementation of such solution.

Question 2 had showed split results. Some see the electrification of remote communities as a very positive input. Others believed isolated communities had already what they needed, as they had been successfully surviving without electricity for centuries with good livelihood, and a new technology could unbalance a remote community and generate unexpected problems.

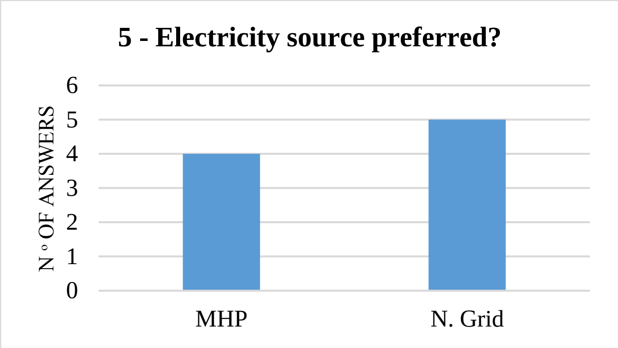
Questions 3 and 4

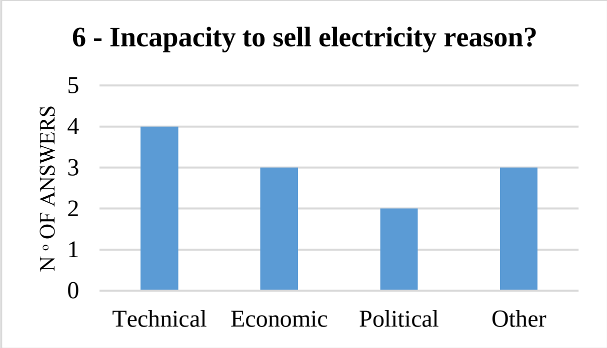


While undergoing informal interviews, multiple negative livelihood impacts were pointed out when trying to understand the effects on the livelihood of isolated communities after the implementation of a MHP scheme: increased hours watching TV, unbalanced re-distribution of work hours and higher differentiation between classes (i.e., some people can't pay the electricity tariff) among others. Nevertheless, the positive inputs seemed more numerous. The experts seemed to show strong agreement that MHP equals better livelihoods.

Question 4 shows that the no specific reason is behind the most common failure reasons. Perhaps better overall engineering design, construction and operation and maintenance is required.

Questions 5 and 6

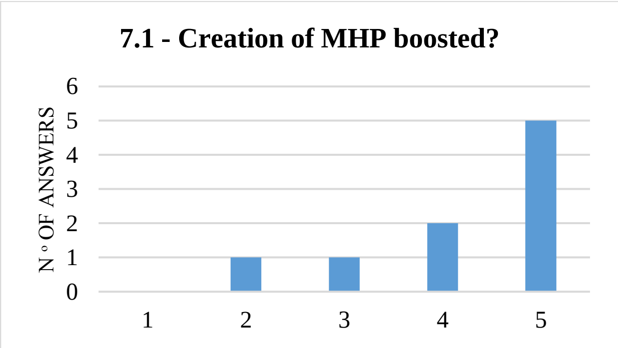


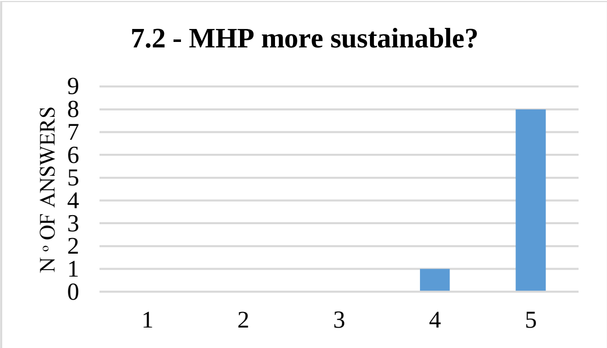


When comparing the unreliable but cheap and continuous MHP power, to the reliable and expensive but non-continuous (i.e., 8 hours a day) national grid, the division in the opinion of experts was similar to the division of the households that had the possibility of connecting to both systems, as seen in Baglung mini-grid case study.

Question 6 revealed that the reasons why MHP cannot connect to the national grid are unclear.. An expert working for the governmental organization in charge (AEPC) confirmed that on July 2014 a new policy allowed for small producers (under 100kW) to sell back to the grid, but commented on such policy, stating that it was the economic (extension of national grid) and technical difficulties (synchronization problems) that were preventing small production to happen, noting that only 3 MHP schemes in all the country had applied for such license.

Questions 7.1 and 7.2

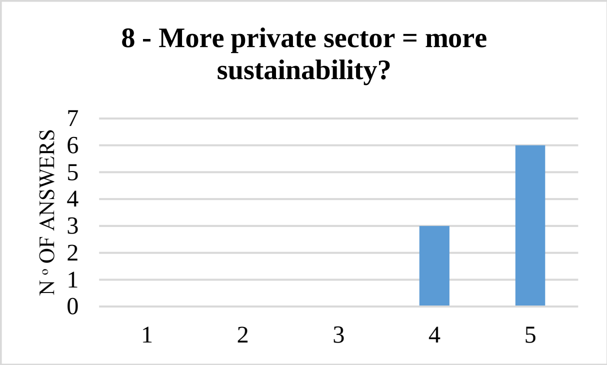




Result show clearly that if small generation could be more easily sold to the national grid more schemes would be created, as they would not only generate electricity, but also an income.

The clear answer of question 7.2 can lead to think that the overall sustainability of a scheme is very directly related to the economic resources to sustain it.

Question 8



After one year of construction, full ownership and maintenance of the scheme are passed to the community, and administrated by the users committee. Experience in Nepal has shown that the lack of knowledge to deal with such engineering solution has led to the decay of schemes. Experts agree that involving the private sector past the one year mark would increase the scheme sustainability.

ANNEX B – Schemes synopsis

Yearly Rainfall

Yearly rainfall in the most representative regions of the four studied countries (Figure B1).

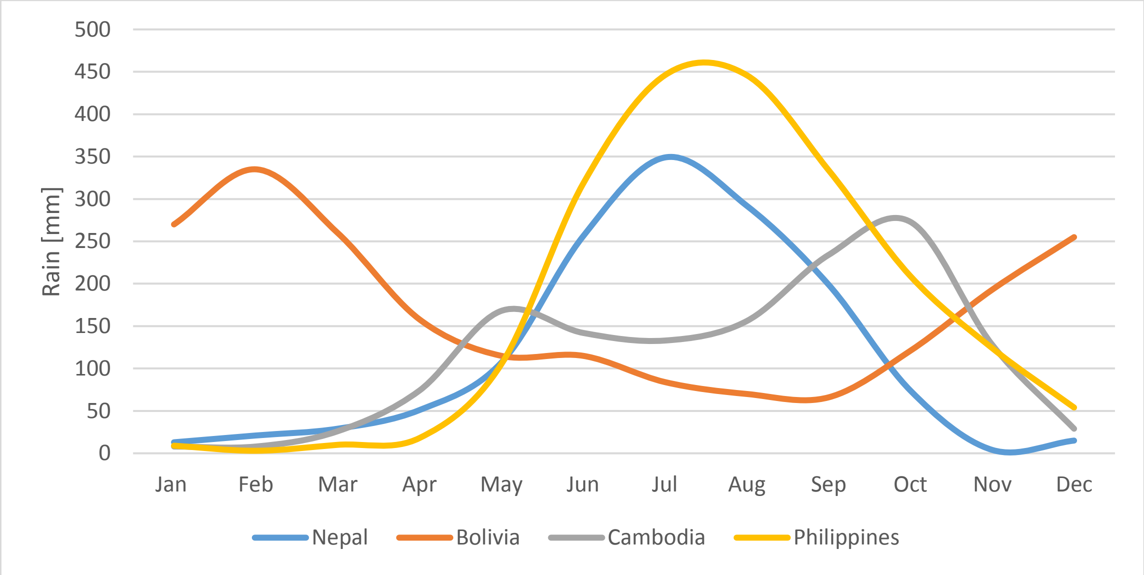


Figure B1. Yearly rainfall for the four suited schemes.

Synopsis of the schemes visited in Nepal

Table B1. Synopsis of NP.1 scheme.

Synopsis of Bhussinga Micro Hydro Project				
Site file:	NP1- Bhussinga		**Location:**	Bhussinga VDC, in the meeting point of Ramechhap, Okhaldhunga and Solukhumbu
Visit date:	10st of February , 2015		**GPS:**	27.49, 86.39
PARAMATER		**VALUE**	**COMMENTS**	
$Head_g$:70	**$Head_n$**	: 66 m		
Design flow		: 240 lps		
Designed power output		: 75kW		
Actual power output		: 86kW	Pre-feasibility report value is always lower.	
Overall efficiency		: 55%		
Length headrace		: 500 m		
Length penstock		: 95 m	Angle 45º	
Turbine		: Crossflow		
Generator		: ---		
Transmission length		: ---		
Project total cost		: ---		
Cost/kW		: ---		
Electrified date		: 2013		
Ownership		: Community		
End-use HHs		: 745		
End-use others		:		
NOTES				

Figure B1. NP.1 Forebay tank.

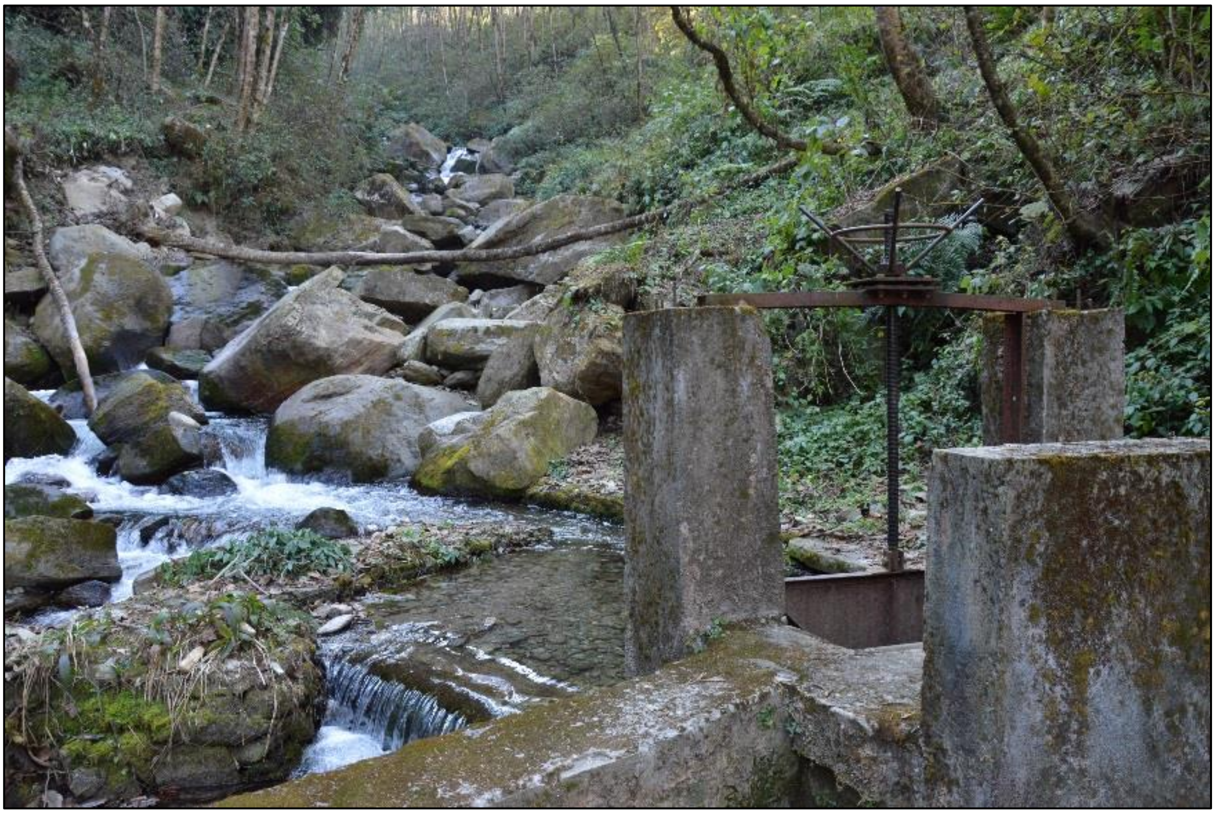


Figure B2. NP.1 Intake structure.

Table B2. Synopsis of NP.2 scheme.

<table>
<tr><th colspan="3">Synopsis of Karamdanda Micro Hydro Project</th></tr>
<tr><td>Site file: NP2- Karamdanda</td><td></td><td>Location Kavre, Bhimkhori VDC, by the BP highway.</td></tr>
<tr><td>Visit date: 28st of February ,2015</td><td></td><td>GPS: 27.44, 85.77</td></tr>
<tr><th>PARAMATER</th><th>VALUE</th><th>COMMENTS</th></tr>
<tr><td>Head_g :13.75m Head_n</td><td>: 13.01m</td><td>Approx. 45 º</td></tr>
<tr><td>Design flow</td><td>: 216 lps</td><td>Measured with Salt dilution method</td></tr>
<tr><td>Designed power output</td><td>: 16kW</td><td></td></tr>
<tr><td>Actual power output</td><td>: 17kW</td><td></td></tr>
<tr><td>Overall efficiency</td><td>: 55%</td><td></td></tr>
<tr><td>Length headrace</td><td>: 1447m</td><td></td></tr>
<tr><td>Length penstock</td><td>: 23m</td><td>325 mm ID, Mild Steel, 3mm thick, Approx. 45 º</td></tr>
<tr><td>Turbine</td><td>: Crossflow</td><td>22kW Shaft output</td></tr>
<tr><td>Generator</td><td>: Sync.35KVA</td><td>1500 rpm 3Ph</td></tr>
<tr><td>Transmission length</td><td>: 4630 m</td><td></td></tr>
<tr><td>Project total cost</td><td>: 4,129,905</td><td>56,574 NZD</td></tr>
<tr><td>Cost/kW</td><td>: 242,935</td><td>3,328 NZD</td></tr>
<tr><td>Electrified date</td><td>: 7/9/2010</td><td></td></tr>
<tr><td>Ownership</td><td>: Community</td><td></td></tr>
<tr><td>End-use HHs</td><td>: 179</td><td>Initially 138, changes form the pre-feasibility</td></tr>
<tr><td>End-use others</td><td>: 5</td><td>Mec: Huller, grinder// Elec: saw-mill, bakery. // Telecommunications tower</td></tr>
<tr><th colspan="3">NOTES</th></tr>
<tr><td colspan="3">The scheme has two main users:
1- The village with the 179 HH, they pay 100 NPR/month, for 100 W
2- 2- A telecom company that has a tower up the hill, 12000 NPR/month.</td></tr>
<tr><td colspan="3">It is maintained by two operators, with the main one earning 7000 NRP and the second 3000. There are approx. 1000 NRP/month as general maintenance. The remaining 14000 NPR go to a bank account, for future maintenance/improvements.</td></tr>
<tr><td colspan="3">A number of e end-uses: mechanically, as seen in pictures, a huller (rice processing), grinder (corn), and electrically a saw-mill and a bakery.</td></tr>
<tr><td colspan="3">A landslide that covered partially the headrace was the only major damage</td></tr>
</table>

Figure B3. NP.2 Desilting tank.

Figure B4. NP.2 Corn mill mechanically powered by the MHP.

Table B3. Synopsis of NP.3 scheme.

Synopsis of Chhange Khola Micro Hydro Project		
Site file: NP3- Chhange Khola		**Location** Sindhuli, KusheshworcDumja, by the BP highway, 49km of Dhulikhel
Visit date: 28st of February ,2015		**GPS:** 27.41, 85.80
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:210 **Head$_n$**	: 199.5m	
Design flow	: 14.5 lps	
Designed power output	: 16kW	Only 11kW are used by the community.
Actual power output	: 16kW	
Overall efficiency	: 56%	
Length headrace	: 650m	HDPE
Length penstock	: 280m	Variable angle 30-60°
Turbine	: Pelton	
Generator	: Sync.30KVA	1500 rpm 3Ph
Transmission length	: 3900 m	
Project total cost	: 5,384,400NPR	73,759 NZD
Cost/kW	: 336,525NPR	4.610 NZD
Electrified date	: 11/9/2011	
Ownership	: Community	
End-use HHs	: 140	F470, M434
End-use others	: 2	Two grain mills, form tailrace.
NOTES		
The scheme has one main user, households paying 150 NPR per month for 100W, from 6 pm to 6am.		
It is maintained by two operators, one at the powerhouse, the other one at the top, intake, silt basin and forebay structure. The water comes from a spring, so very little maintenance due to silt.		
A landslide destroyed part of the HDPE pipe, needed full replacement of the section.		
The village has 126 biogas plants, as seen in pictures. They also had 17 Solar Home System SHS before they had the MHP. Presence of 11 Improved Cooking Systems ICS		

Figure B5. NP.3 Penstock and powerhouse.

Table B4. Synopsis of NP.4 scheme.

Synopsis of Urja 1 Micro Hydro Project		
Site file: NP4- B. Urja 1		**Location** Rangkhani-1 Rumta, Baglung
Visit date: 12st of March 2015		**GPS:** 28.16, 83.57
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 54 m **Head$_n$**	:	
Design flow	: 100 lps	
Designed power output	: 26kW	
Actual power output	: 25kW	Slight performance reduction after 15 years.
Overall efficiency	: 49%	
Length headrace	: 625m	
Length penstock	:	Mild steel
Turbine	: Crossflow	
Generator	: Sync.50KVA	1500 rpm 3Ph
Transmission length	: 5300 m	4500 m 3 phase & 800 m 1 phase
Project total cost	: 4,072,744NPR	55.791 NZD
Cost/kW	: 156,644 NPR	2.145 NZD
Electrified date	: 2000	
Ownership	: Community	
End-use HHs	: 272	
End-use others	: 11	1 Ncell tower, 2 electric shops, 3 mills, 1 computer centres, 4 poultries
NOTES		
Function 22h, couple of hours to rest machinery, maintenance, but the Ncell tower needs the rest of the day.		
It is maintained by two operators. Price for users: 75 Rs for a unit, and then 7 Rs for any extra unit.		
Maintenance: grease once every two months; in summer leaves every day; sluice gate once per month in rain season and once every two or three months in dry season.		
In summer, for a few days, the scheme takes enough water to leave the main river without enough water.		

Figure B6. NP.4 Intake structure.

Figure B7. NP.4 Steel penstock.

Table B5. Synopsis of NP.5 scheme.

Synopsis of Urja 2 Micro Hydro Project		
Site file: NP5- B. Urja 2		**Location** Rangkhani-1 Chicapani, Baglung
Visit date: 12st of March 2015		**GPS:** 28.16, 83.58
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 17 m **Head$_n$**	:	
Design flow	: 120 lps	
Designed power output	: 9kW	
Actual power output	: 10.5W	Under-designed
Overall efficiency	: 52%	
Length headrace	: 195m	
Length penstock	:	Mild steel
Turbine	: Crossflow	
Generator	: Sync.20KVA	1500 rpm 3Ph
Transmission length	: 2000 m	1500 m 3 phase & 500 m 1 phase
Project total cost	: 2,889,800NPR	39.586 NZD
Cost/kW	: 275,219NPR	3.770 NZD
Electrified date	: 2003	
Ownership	: Community	
End-use HHs	: 158	
End-use others	: 6	2 mills, 2 schools, 2 poultries
NOTES		
The water comes mainly from the tailrace of Urja 1. Some water is added from another upper stream.		
It is maintained by two operators. The scheme was designed for a design flow of 11 months.		
Sluice gate opened twice per year (probably due to the water coming from the Urja 1)		
Fishermen use electricity to electrocute fish		

Figure B8. NP.5 Forebay tank, steel penstock and powerhouse.

Figure B9. NP.5 Powerhouse with electric equipment for the Baglung mini-grid.

Table B6. Synopsis of NP.6 scheme.

<table>
<tr><th colspan="4">Synopsis of Kalung Micro Hydro Project</th></tr>
<tr><td>Site file:</td><td>NP6- B. Kalung</td><td colspan="2">Location Paiyauthanthap-4, Lamsu, Baglung</td></tr>
<tr><td>Visit date:</td><td>13st of March 2015</td><td colspan="2">GPS: 28.16, 83.56</td></tr>
<tr><th colspan="2">PARAMATER</th><th>VALUE</th><th>COMMENTS</th></tr>
<tr><td colspan="2">Head_g : 58 m Head_n</td><td>: 56 m</td><td></td></tr>
<tr><td colspan="2">Design flow</td><td>: 70 lps</td><td></td></tr>
<tr><td colspan="2">Designed power output</td><td>: 22kW</td><td></td></tr>
<tr><td colspan="2">Actual power output</td><td>: 22kW</td><td></td></tr>
<tr><td colspan="2">Overall efficiency</td><td>: 55%</td><td></td></tr>
<tr><td colspan="2">Length headrace</td><td>: 550m</td><td></td></tr>
<tr><td colspan="2">Length penstock</td><td>:</td><td>Mild steel</td></tr>
<tr><td colspan="2">Turbine</td><td>: Pelton</td><td>Double jet</td></tr>
<tr><td colspan="2">Generator</td><td>: Sync.40KVA</td><td>1500 rpm 3Ph</td></tr>
<tr><td colspan="2">Transmission length</td><td>: 3000 m</td><td>2000 m 3 phase & 1000 m 1 phase</td></tr>
<tr><td colspan="2">Project total cost</td><td>: 4,928,226NPR</td><td>67,509 NZD</td></tr>
<tr><td colspan="2">Cost/kW</td><td>: 224,010NPR</td><td>3,068 NZD</td></tr>
<tr><td colspan="2">Electrified date</td><td>: 1999</td><td></td></tr>
<tr><td colspan="2">Ownership</td><td>: Community</td><td></td></tr>
<tr><td colspan="2">End-use HHs</td><td>: 230</td><td></td></tr>
<tr><td colspan="2">End-use others</td><td>: 3</td><td>3 mills</td></tr>
<tr><th colspan="4">NOTES</th></tr>
<tr><td colspan="4">The penstock has several leaks, and no intention of repairing them exist.</td></tr>
<tr><td colspan="4">ELC replacement. The scheme was designed for a design flow of 11 months.</td></tr>
<tr><td colspan="4">Working only from 5pm to 12 night and from 4 am to 11 am.</td></tr>
<tr><td colspan="4">Leaves twice per day in summer, sluice gate once per month.</td></tr>
</table>

Figure B10. NP.6 Steel penstock and powerhouse.

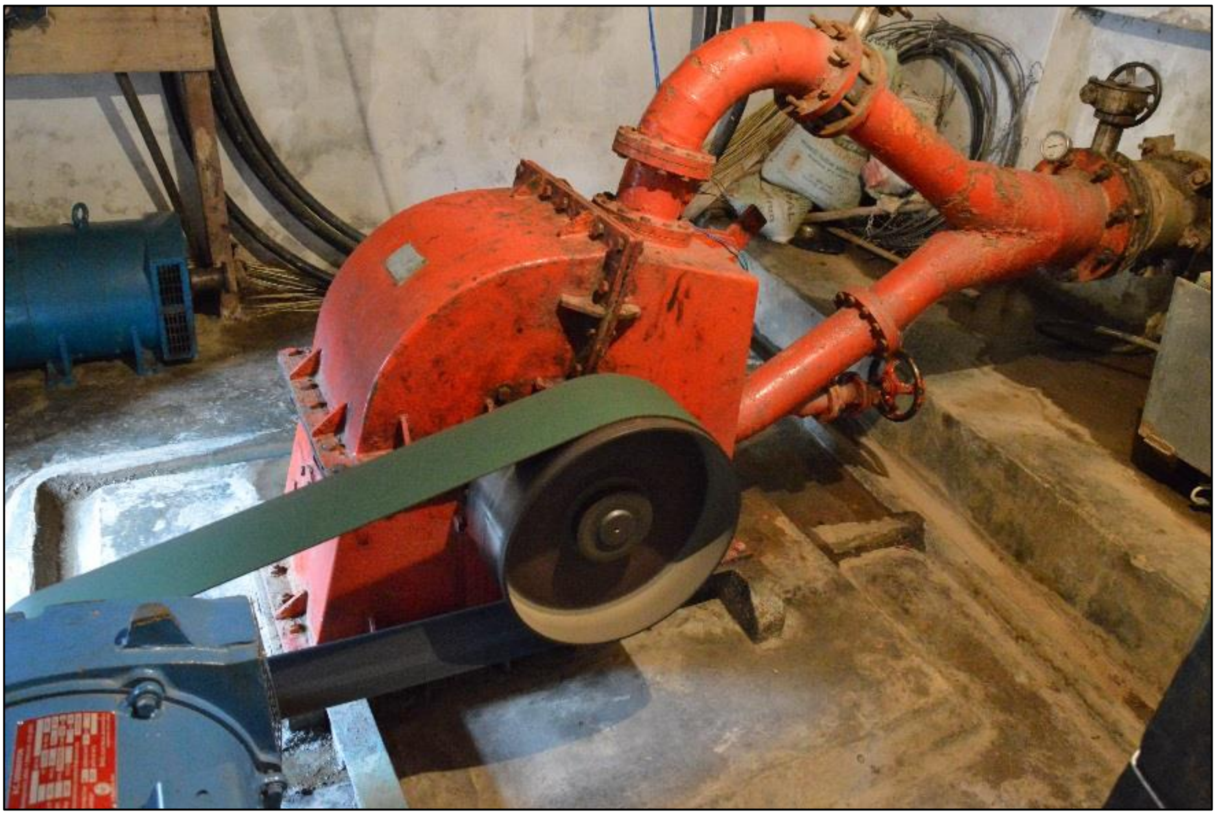


Figure B11. NP.6 Twin-jet Pelton turbine.

Table B7. Synopsis of NP.7 scheme.

Synopsis of Upper Kalung Micro Hydro Project		
Site file: NP7- B. Upper Kalung		**Location** Paiyauthanthap-9, Bijua, Baglung
Visit date: 13st of March 2015		**GPS:** 28.17, 83.55
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 57.5 m **Head$_n$**	: 57 m	
Design flow	: 45 lps	
Designed power output	: 12kW	
Actual power output	: 15kW	10kW in dry season.
Overall efficiency	: 61%	
Length headrace	: 345m	
Length penstock	:	Mild steel
Turbine	: Crossflow	
Generator	: Sync.25KVA	1500 rpm 3Ph
Transmission length	: 2200 m	1200 m 3 phase & 1000 m 1 phase
Project total cost	: 4,029,360NPR	55,197 NZD
Cost/kW	: 268,624NPR	3,680 NZD
Electrified date	: 2005	
Ownership	: Community	
End-use HHs	: 115	
End-use others	: 6	2 Agro-processing mills, 2 poultry, 2 computer rooms
NOTES		
Only working from 4 am to 10 am, 1pm to 4pm, 6pm to 11pm		
The scheme was designed for a design flow of 11 months.		
They use the electricity generated to kill the fish. ELC replacement, relays		
Sluice gate once per year, greasing 4 times a year.		

Figure B12. NP.7 Steel penstock and powerhouse.

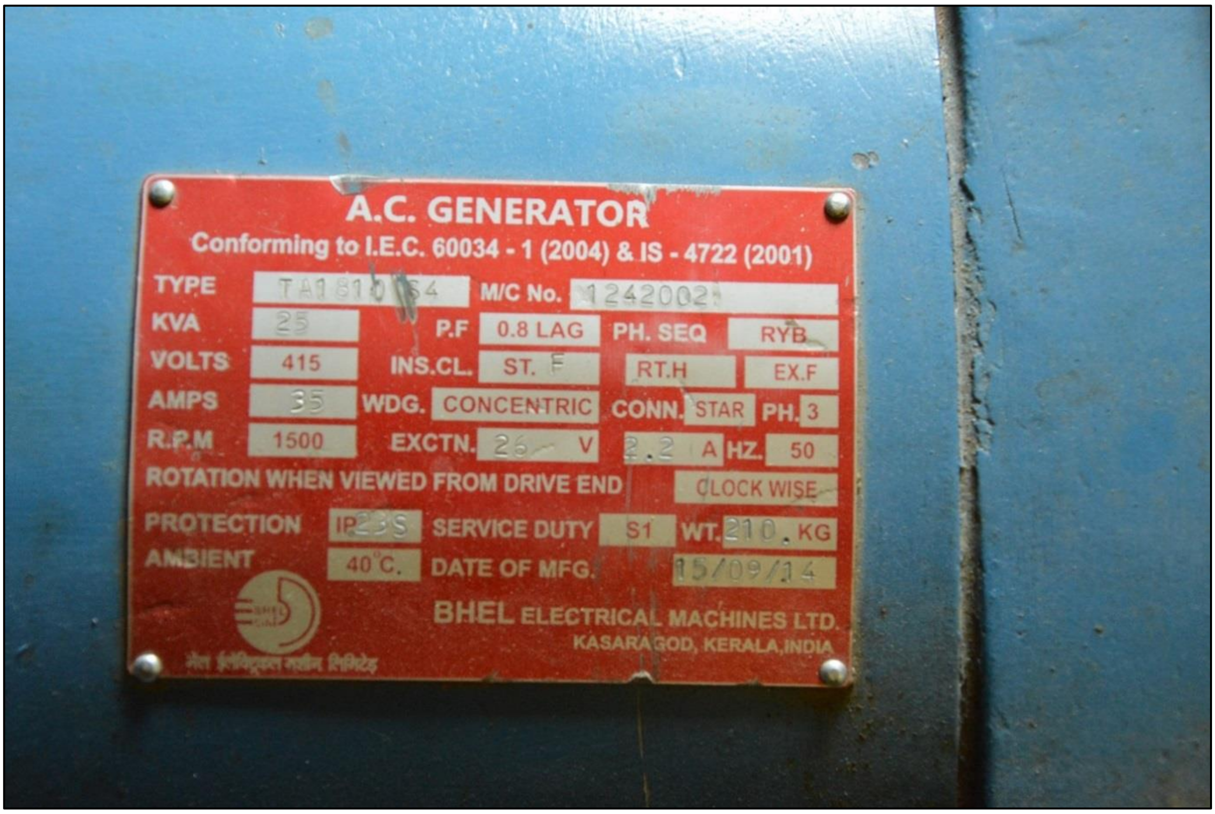


Figure B13. NP.7 Generator specifications.

Table B8. Synopsis of NP.8 scheme.

Synopsis of Urja 4 Micro Hydro Project		
Site file: NP8- B. Urja 4		**Location** Damek, Zadi, Baglung
Visit date: 13^{st} of March 2015		**GPS:** 28.17, 83.60
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 16 m **Head$_n$** :		
Design flow	: 162 lps	
Designed power output	: 14kW	Only 11kW are used by the community.
Actual power output	: 12,5 kW	Slight performance reduction after 15 years.
Overall efficiency	: 49%	
Length headrace	: 250m	
Length penstock	:	Mild steel
Turbine	: Crossflow	
Generator	: Sync.30KVA	1500 rpm 3Ph
Transmission length	: 4000 m	3000 m 3 phase & 1000 m 1 phase
Project total cost	: 5,092,500NPR	69.760 NZD
Cost/kW	: 407,400NPR	4,983 NZD
Electrified date	: 2011	
Ownership	: Community	
End-use HHs	: 133	
End-use others	: 2	2 Agro-processing mills, 1 saw mill
NOTES		
3 hours of maintenance only.		
It is maintained by two operators + the expert operator of Urja 1		
The scheme was designed for a design flow of 11 months. (problems with water for dry season)		
Sluice gate open once or twice per month, more in wet season.		

Figure B14. NP.8 Canal, subterranean pipe, and forebay tank.

Figure B15. NP.8 Electromechanical group.

Table B9. Synopsis of NP.9 scheme.

Synopsis of Theule Khola Micro Hydro Project		
Site file: NP9- B. Theule Khola		**Location** Sarkuwa-9, Rumti, Baglung
Visit date: 13st of March 2015		**GPS:** 28.18, 83.61
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 32 m **Head$_n$**	:	
Design flow	: 150 lps	
Designed power output	: 24 kW	
Actual power output	: 24 kW	
Overall efficiency	: 51%	
Length headrace	: 550m	
Length penstock	:	Mild steel
Turbine	: Crossflow	
Generator	: Sync.56KVA	1500 rpm 3Ph
Transmission length	: 3000 m	2500 m 3 phase & 500 m 1 phase
Project total cost	: 4,682,594NPR	64,145 NZD
Cost/kW	: 195,056NPR	2672 NZD
Electrified date	: 1999	
Ownership	: Community	
End-use HHs	: 290	
End-use others	: 7	4 mills, 3 poultries
NOTES		
Sluice gate 1 every week in rainy season, 1 every 2-3 months in dry season.		
It is maintained by one operator and a private operator from a company		
More power could be generated, water enough.		
Replacement of ELC and AVR (automatic voltage regulator)		

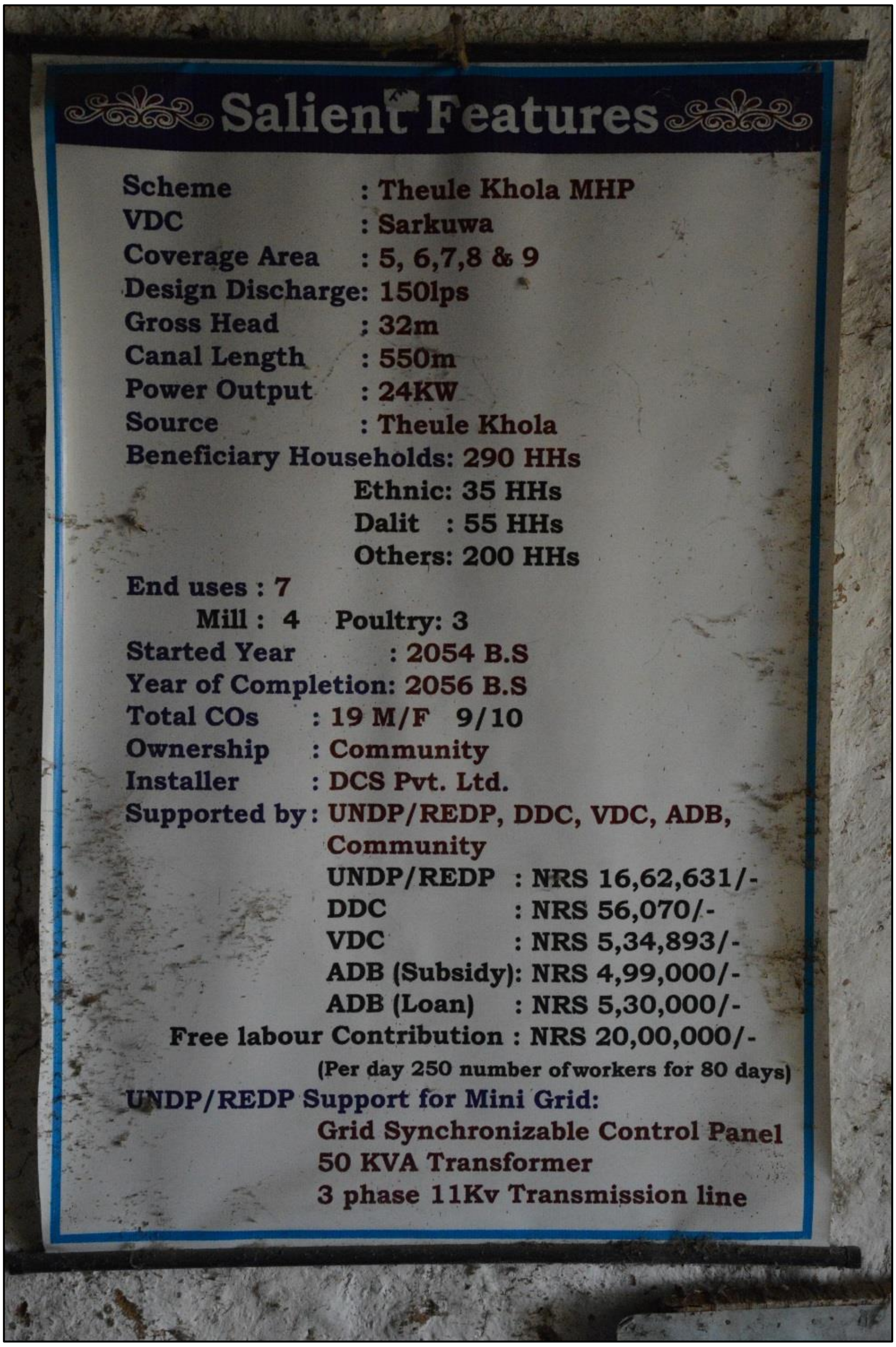


Figure B16. NP.9 Scheme salient features displayed at powerhouse.

Table B10. Synopsis of NP.10 scheme.

Synopsis of Kushadevi Micro Hydro Project			
Site file: NP10- Kushadevi		**Location**	Kushadevi, Kabhrepalanchok District
Visit date: 17st of March 2015		**GPS:**	27.59, 85.49
PARAMATER	**VALUE**	**COMMENTS**	
Head$_g$: --- **Head$_n$**	: 2.5 m		
Design flow	: 45 lps		
Designed power output	: 500 W		
Actual power output	: ---		
Overall efficiency	: 45%		
Length headrace	: 1379 m		
Length penstock	: 4 m	HDPE	
Turbine	: Turgo like	Banepa local produced Turgo like turbine	
Generator	: Ind.	Induction type 3Ph, 50Hz.	
Transmission length	: ---	---	
Project total cost	: 12000NPR	164 NZD (price 48 years back)	
Cost/kW	: 24,000NPR	329 NZD	
Electrified date	: 1966		
Ownership	: Community		
End-use HHs	: 11		
End-use others	: 1	1 agro mill, attached to the short shaft	
NOTES			
Gabion structure moved in a flood last wet season, June 2014, nothing working since then.			
It is maintained by one operator and people from the VDC water mill association.			
The system has potential for much more, as the river is perennial and 200-300 l/s could be extracted without problems.			
The community has huge concern due to the lack of reliability, and most prefer the national grid that passes nearby.			

Figure B17. NP.10 Locally made turbine.

Figure B18. NP.10 Grain mill, powered electrically by the MHP scheme.

Synopsis of the schemes visited in Bolivia

Table B11. Synopsis of BO.1 scheme.

Synopsis of Uma Palca Micro Hydro Project		
Site file: BO1- Uma Palca		**Location** Beginning of municipio Guanay, Larecaja, La Paz
Visit date: 28th of September 2015		**GPS:** -16.05, -68.2167
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:50 **Head$_n$**	: 46 m	
Design flow	: 50 lps	Unknown number, estimated from kW
Designed power output	: 12kW	
Actual power output	: 6kW	Pre-feasibility report value is always lower.
Overall efficiency	: 25%	
Length headrace	: 180 m	
Length penstock	: 114 m	
Turbine	: Pelton 2jet	The lower jet is not aligned.
Generator	: 40kVA	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2008	
Ownership	: Community	
End-use HHs	: 25	TV, small appliances, lighting
End-use others	: 0	That's why they are upgrading
NOTES		
Ideal physical conditions, with river with plenty of water passing 50m on top, next to the community.		
A rotation maintenance system has damaged the overall maintenance. Once per month a different person of the community will do the cleaning/emptying of the forebay and desilting tanks. No one really knows much about the scheme, consequently.		

Figure B19. BO.1 Polyethylene penstock and powerhouse.

Figure B20. BO.1Intake structure.

Table B12. Synopsis of BO.2 scheme.

Synopsis of Tuni Micro Hydro Project		
Site file: BO2- Tuni		**Location** Tuni, Pucarani, Los Andes, La Paz
Visit date: 2nd of October 2015		**GPS:** -16.25, -68.25
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:55 **Head$_n$**	: 53 m	
Design flow	: 25 lps	
Designed power output	: 8kW	
Actual power output	: ---	
Overall efficiency	: 60%	
Length headrace	: 2km	
Length penstock	: 110 m	
Turbine	: Pelton 2jet	
Generator	: ---	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2014	
Ownership	: Community	
End-use HHs	: 14	TV, small appliances, lighting
End-use others	: 2	2 eco-lodges.
NOTES		
Quasi Ideal physical conditions, with existing channel with good amounts of water passing 50 on top,100-150 m from the community.		
Maintenance done by a family. Woman unable to do it, as they did not catch up with the training.		

Figure B21. BO.2 Headrace.

Figure B22. BO.2 ELC resistors in water tank.

Table B13. Synopsis of BO.3 scheme.

Synopsis of Huayna Potosi Micro Hydro Project		
Site file: BO3- Huayna Potosi		**Location** Huayna Potosi, Pucarani, Los Andes, La Paz
Visit date: 3nd of October 2015		**GPS:** -16.279808, -68.176756
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:40 **Head$_n$**	: --	
Design flow	: 10 lps	
Designed power output	: 2kW	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 200km	Earth channel causing lots of erosion.
Length penstock	: 190 m	
Turbine	: Pelton 2jet	Only one needle, on top.
Generator	: ---	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2013	
Ownership	: Family	Guillermo, in charge of the Eco-lodge.
End-use HHs	: 1	TV, small appliances, lighting
End-use others	: 1	1 eco-lodges.
NOTES		
ELC probably not working, as frequency needed adjusting by hand, by opening or closing the needle.		
Poor quality of concrete making civil works useless.		
Earth channel creating a lot of erosion.		
Complete diversion of the river.		

Figure B23. BO.3 Forebay tank.

Figure B24. BO.3 PVC headrace bridge.

Table B14. Synopsis of BO.4 scheme.

Synopsis of Challa Micro Hydro Project		
Site file: BO4- Challa		**Location** Challa, Coroico, Nor Yungas, La Paz
Visit date: 14th of October 2015		**GPS:** -16.0922, -67.6968
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:168 **Head$_n$**	: 160	
Design flow	: 84 lps	
Designed power output	: 100kW	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	:	System of pipes and depots
Length penstock	:	
Turbine	: Pelton 1jet	
Generator	: ---	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2000	
Ownership	: Village	
End-use HHs	:	
End-use others	:	
NOTES		
The intake is too far away, too high, maintenance problems, with landslides, made the scheme impossible to maintain.		

Figure B25. BO.4 Pelton turbine and generator.

Figure B26. BO.4 Headrace tank covered and damaged by vegetation.

Table B15. Synopsis of BO.5 scheme.

Synopsis of Chojna Micro Hydro Project			
Site file: BO5 – Chojna		**Location**	Chojna, Caranabi, Nor Yungas, La Paz
Visit date: 17th of October 2015		**GPS:**	-15.9541, -67.5693
PARAMATER	**VALUE**	**COMMENTS**	
$Head_g$:134 **$Head_n$**	128		
Design flow	: 20 lps		
Designed power output	: 16kW		
Actual power output	: ---		
Overall efficiency	: ---		
Length headrace	: 15m		
Length penstock	: 675		
Turbine	: Pelton 1jet		
Generator	: 30 KVA		
Transmission length	: ---		
Project total cost	: ---		
Cost/kW	: ---		
Electrified date	: 1998		
Ownership	: Village		
End-use HHs	: 30		
End-use others	: 0	Not enough energy	
NOTES			
Also some complains about the distance from the village to the source of water.			

Figure B27. BO.5 Pelton turbine with degradation marks.

Figure B28. BO.5 Tri-phasic electric lines covered in vegetation.

Table B16. Synopsis of BO.6 scheme.

<table>
<tr><th colspan="6">Synopsis of 18 de Mayo Micro Hydro Project</th></tr>
<tr><td colspan="2">Site file:</td><td colspan="2">BO6 – 18 de Mayo</td><td>Location:</td><td>18 de Mayo, Caranabi, Nor Yungas, La Paz</td></tr>
<tr><td colspan="2">Visit date:</td><td colspan="2">18th of October 2015</td><td>GPS:</td><td>-15.9442, -67.5708</td></tr>
<tr><th colspan="3">PARAMATER</th><th>VALUE</th><th colspan="2">COMMENTS</th></tr>
<tr><td>Head_g</td><td>:96</td><td>Head_n</td><td>92</td><td colspan="2"></td></tr>
<tr><td colspan="3">Design flow</td><td>: 15 lps</td><td colspan="2"></td></tr>
<tr><td colspan="3">Designed power output</td><td>: 8kW</td><td colspan="2"></td></tr>
<tr><td colspan="3">Actual power output</td><td>: ---</td><td colspan="2"></td></tr>
<tr><td colspan="3">Overall efficiency</td><td>: ---</td><td colspan="2"></td></tr>
<tr><td colspan="3">Length headrace</td><td>: 650</td><td colspan="2">Underground PVC</td></tr>
<tr><td colspan="3">Length penstock</td><td>: 300</td><td colspan="2">PVC, underground too.</td></tr>
<tr><td colspan="3">Turbine</td><td>: Pelton 1jet</td><td colspan="2"></td></tr>
<tr><td colspan="3">Generator</td><td>: 20 KVA tri</td><td colspan="2"></td></tr>
<tr><td colspan="3">Transmission length</td><td>: ---</td><td colspan="2"></td></tr>
<tr><td colspan="3">Project total cost</td><td>: ---</td><td colspan="2"></td></tr>
<tr><td colspan="3">Cost/kW</td><td>: ---</td><td colspan="2"></td></tr>
<tr><td colspan="3">Electrified date</td><td>: 2000</td><td colspan="2"></td></tr>
<tr><td colspan="3">Ownership</td><td>: Village</td><td colspan="2"></td></tr>
<tr><td colspan="3">End-use HHs</td><td>: 40</td><td colspan="2"></td></tr>
<tr><td colspan="3">End-use others</td><td>: 0</td><td colspan="2">Not enough power</td></tr>
<tr><th colspan="6">NOTES</th></tr>
<tr><td colspan="6">They extracted the headrace pipe for sewage system.</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6"></td></tr>
</table>

Figure B29. BO.6 Forebay tank covered by vegetation.

Figure B30. BO.6 Penstock covered by dead vegetation.

Table B17. Synopsis of BO.7 scheme.

Synopsis of La Cascada de Mayo Micro Hydro Project		
Site file: BO7 – La Cascada		**Location** La Cascada, Sud Yungas, Beni
Visit date: 21th of October 2015		**GPS:** -15.3887, -67.1174
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:73 **Head$_n$**	:69	
Design flow	: 90 lps	
Designed power output	: 40kW	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 700	Floating pipe system, through the forest
Length penstock	: 135	PVC ESQ 40
Turbine	: Pelton 1jet	
Generator	: 87 KVA tri	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2002	
Ownership	: Village	
End-use HHs	: 120	
End-use others	: 0	Not enough power
NOTES		
Powerhouse used for Tumupasa.		
Pelton needed replacement, and ELC too.		

Figure B31. BO.7 Abandoned intake structure.

Figure B32. BO.7 Lumber mill electrically powered.

Table B18. Synopsis of BO.8 scheme.

Synopsis of Tumupasa de Mayo Micro Hydro Project		
Site file: BO8 – Tumupasa		**Location** Tumupasa, San Buenaventura, La Paz
Visit date: 28th of October 2015		**GPS:** -14.15, -67.89
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:81 **Head$_n$**	:78	
Design flow	: 80 lps	
Designed power output	: 40kW	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 1800	
Length penstock	: 150	120 PVC+30 galvanized iron.
Turbine	: Pelton 1jet	47 kW
Generator	: 90 KVA tri	
Transmission length	: ---	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2000	
Ownership	: Village	
End-use HHs	: 180	
End-use others	: 0	Not enough power
NOTES		
In 2007 they needed tor replace most of the power house and build a reservoir due to lack of water.		
They had diesel generators for when de MHP was not working.		

Figure B33. BO.8 Concrete headrace covered by vegetation.

Table B19. Synopsis of BO.9 scheme.

Synopsis of Cotacajes de Mayo Micro Hydro Project		
Site file: BO9- Cotacajes		**Location** Cotacajes, Morochata, Cochabamba
Visit date: 10th of November 2015		**GPS:** -16.74, -66.74
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:36 **Head$_n$**	:34	
Design flow	: 180 lps	
Designed power output	: 35kW	
Actual power output	: 35 or more	
Overall efficiency	: ---	
Length headrace	: 500	
Length penstock	: 60	PVC
Turbine	: Crossflow	35kW
Generator	: 54.6 KVA	
Transmission length	:	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2014	
Ownership	: Village	
End-use HHs	: 60	
End-use others	: 4	Carpentry, water pump, welding, rice peeler machine
NOTES		

Figure B34. BO.9 Headrace diversion system.

Figure B35. BO.9 Improvised intake structure.

Table B20. Synopsis of BO.10 scheme.

Synopsis of Pucara de Mayo Micro Hydro Project		
Site file: BO10- Pucara		**Location** Pucara, Vallegrande, Santa Cruz
Visit date: 14th of November 2015		**GPS:** -18.7190, -64.1838
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:126 **Head$_n$**	:120	
Design flow	: 170 lps	
Designed power output	: 122kW	
Actual power output	: <100kW	
Overall efficiency	:	
Length headrace	: >1km	
Length penstock	:	
Turbine	: Crossflow	
Generator	:	
Transmission length	:	
Project total cost	: ---	
Cost/kW	: ---	
Electrified date	: 2007	
Ownership	: Village	
End-use HHs	: 313	Finished with 432
End-use others	:	
NOTES		

Figure B36. BO.10 Forebay tank.

Synopsis of the schemes visited in Cambodia

Table B21. Synopsis of CA.1 scheme.

Synopsis of Sek Sok Micro Hydro Project		
Site file: CA1 – Sek Sok		**Location** Sek Sok, Treng, Battambang
Visit date: 5th of June 2016		**GPS:** 12.7691, 102.8919
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:2m **Head$_n$**	: ---	
Design flow	: 1000 lps	Estimation
Designed power output	: 12kW	Estimation
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 10 m	
Turbine	: Propeller	
Generator	: mono	
Transmission length	: 200	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2011	
Ownership	: Single owner	
End-use HHs	: 5	
End-use others	: 1	Resort
NOTES		
No lack of water.		
Second turbine for rainy season only, although it never came to realization.		

Figure B37. CA.1 Intake structure, 2 metal penstocks and structure to support the generators.

Figure B38. CA.1 Correcting belts and generators for the two turbines.

Table B22. Synopsis of CA.2 scheme.

Synopsis of Koh Sampeay Micro Hydro Project			
Site file:	CA2 – Koh sampeay	**Location**	Koh Sampeay Village, Stung Treng
Visit date:	9th of June 2016	**GPS:**	13.425146, 105.95583
PARAMATER	**VALUE**	**COMMENTS**	
Head$_g$:2.5m **Head$_n$** :			
Design flow	: 1300 lps	Unknown number, estimated from kW and video	
Designed power output	: 16kW		
Actual power output	: 8kW	They said several failures had brought power a lot down.	
Overall efficiency	: 50%		
Length headrace	: 0 m		
Length penstock	: 8 m	Buried concrete pipe with steel end.	
Turbine	: Propeller		
Generator	: mono		
Transmission length	: 500		
Project total cost	: 20.000USD		
Cost/kW	: 1250		
Electrified date	: 2011		
Ownership	: Single owner	Used to be the community, but now only one owner.	
End-use HHs	: 25		
End-use others	: 1	The owner has an ice machine.	
NOTES			
Abundance of water in a pond with underground water supply.			
Initially the whole community 20-30 HH was using it. With time, technical/maintenance problems arose, and with the arrival of the national grid, everyone, expect the owner of the land/scheme, switched to the national line. The national grid was cheaper			
No existence of electric protections (fuse box?)			
No lack of water in dry season.			

Figure B39. CA.2 concrete penstock, axial turbine (in blue metallic steel penstock), correcting belt and generator.

Figure B40. CA.2 Pond and intake structure with flow gate.

Table B23. Synopsis of CA.3 scheme.

Synopsis of O'Pongmoan Micro Hydro Project		
Site file: CA3 – O'Pongmoan		**Location** Corner of NH 7 with Rd78, Stung Treng
Visit date: 9th of June 2016		**GPS:** 13.4285, 106.0758
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:2m **Head$_n$**	:	
Design flow	: 1000 lps	Unknown number, estimated from generator kW
Designed power output	: 10kW	
Actual power output	: 10kW	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 10 m	Metallic box
Turbine	: Propeller	
Generator	: mono	
Transmission length	: 200	
Project total cost	:	
Cost/kW	: 1250	
Electrified date	: 2005	
Ownership	: Single owner	He gives electricity to his family members.
End-use HHs	: 4	
End-use others	: 1	Army buildings
NOTES		
He can connect a generator of 30kW if there is more demand.		
He built 3 ram pumps by himself.		
Taught by Japanese. He is involved in the construction of 6 more schemes.		
The tail race is what they suspect feeds Koh Sampeay.		

Figure B41. CA.3 Steel penstock and flow gate and generator.

Figure B42. CA.3 Pond with intake structure and flow gate.

Table B24. Synopsis of O'Romis resort scheme.

Synopsis of O'Romis resort Micro Hydro Project		
Site file: O'Romis resort		**Location** O'Romis, Sen Monorom, Mondulkiri
Visit date: 11th of June 2016		**GPS:** 12.4123, 107.1853
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:1.5m **Head$_n$**	:	
Design flow	: 3x100 lps	Unknown number, estimated from pictures
Designed power output	: 3x1kW	
Actual power output	:	
Overall efficiency	: ---	
Length headrace	: 15 m	
Length penstock	: 1 m	Metallic box
Turbine	: Propeller	
Generator	: mono	
Transmission length	: 0	
Project total cost	:	
Cost/kW	:	
Electrified date	:	
Ownership	: Resort	
End-use HHs	: 1	Resort
End-use others	:	
NOTES		

Figure B43. O'Romis resort water diversion ponded.

Figure B44. O'Romis resort three turbines with generator directly attached.

Table B25. Synopsis of O’Romis scheme.

Synopsis of O'Romis Micro Hydro Project			
Site file:	O'Romis	**Location**	O’Romis, Sen Monorom, Mondulkiri
Visit date:	11th of June 2016	**GPS:**	12.4055, 107.1778
PARAMATER	**VALUE**	**COMMENTS**	
Head$_g$: Head$_n$	: 25.7		
Design flow	: 1.05 lps		
Designed power output	: 215kW		
Actual power output	: 185kW		
Overall efficiency	: 70%		
Length headrace	: 1,024 m	Concrete box	
Length penstock	: 50 m	35+20	
Turbine	: Crossflow	HC-1R2G	
Generator	: mono		
Transmission length	: 5km		
Project total cost	:		
Cost/kW	:		
Electrified date	: 2009		
Ownership	:		
End-use HHs	: 1200		
End-use others	:		
NOTES			
Extra information on pdf file.			

Figure B45. O'Romis penstock and powerhouse and transformer.

Figure B46. O'Romis forebay tank.

Table B26. Synopsis of O'Moleng scheme.

Synopsis of O'Moleng Micro Hydro Project		
Site file: O'Moleng		**Location** O'Moleng, Sen Monorom, Mondulkiri
Visit date: 11th of June 2016		**GPS:** 12.4443, 107.1588
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: Head$_n$	: 18.7	
Design flow	: 1.45 lps	
Designed power output	: 215kW	
Actual power output	: 185kW	
Overall efficiency	: 70%	
Length headrace	: 416 m	Buried pipe 0.6-1 m diameter
Length penstock	: 416 m	
Turbine	: Crossflow	HC-1R2G
Generator	: mono	
Transmission length	: 2km	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2009	
Ownership	:	
End-use HHs	: 1200	
End-use others	:	
NOTES		
Extra information on pdf file.		

Figure B47. O'Moleng powerhouse interior.

Figure B48. O'Moleng intake and forebay tank structure.

Table B27. Synopsis of CA.4 scheme.

Synopsis of Russei Chrum Micro Hydro Project		
Site file: CA4 - Russei Chrum		**Location** Thmor Bang, Koh Kong
Visit date: 14th of June 2016		**GPS:** 11.6872, 103.4419
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:10m **Head$_n$**	:	
Design flow	: 800 lps	Unknown number, estimated from generator kW
Designed power output	: 40kW	
Actual power output	: 40kW	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 50 m	Galvanized rolled iron
Turbine	: Propeller	
Generator	:40kW tri	
Transmission length	: 500m	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2011	
Ownership	: Single owner	He gives electricity to his family members.
End-use HHs	:80	
End-use others	: 0	
NOTES		
In wet season there is enough for people to turn on refrigerators.		
The second gate in the intake is to open it in case of floods. Tailrace meets course of river.		
Received local government funding. They used to run a generator. Which they still run in dry season, if needed.		
50V get lost after 2km of line. The MHP and the bridge were built at the same time.		

Figure B49. CA.4 Electromechanical group.

Figure B50. CA.4 Natural pond with intake with flow gate.

Table B28. Synopsis of CA.5 scheme.

Synopsis of Ouspeu Micro Hydro Project		
Site file: CA 5 - Ouspeu		**Location** Thmor Bang, Koh Kong
Visit date: 15th of June 2016		**GPS:** 11.6851, 103.4308
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:3.5m **Head$_n$** :		
Design flow	: 2x16 lps	Unknown number, estimated from pictures
Designed power output	: 600W	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 10 m	6 inch PVC
Turbine	: 2xPropeller	
Generator	:3kW mono	Estimated
Transmission length	: 50m	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2014	
Ownership	: Single owner	
End-use HHs	:1	
End-use others	: 0	
NOTES		
2 Turbines, 1 in dry season 2 in wet		
Two mechanism exist in the intake area for over flooding, pipes and a ramp.		
He placed the powerhouse in different places until the electricity was good. (right speed for generator, Hz)		
He can light 1 TV + 2 lights or 10 lights with one turbine.		

Figure B51. CA.5 Powerhouse with dual penstock and turbine to adapt to different incoming flows.

Figure B52. CA.5 Natural pond with intake 'structure'.

Table B29. Synopsis of CA.6 scheme.

Synopsis of Lower Tatei Leu Micro Hydro Project		
Site file: CA6 – Lower Tatei Leu		**Location** Lower Tatai Leu, Thmor Bang, Koh Kong
Visit date: 15th of June 2016		**GPS:** 11.7742, 103.4798
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:5m **Head$_n$**	:	
Design flow	: 30 lps	Unknown number, estimated from pictures
Designed power output	: 500W	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 30 m	8 inch PVC?
Turbine	:Propeller	
Generator	:3kW mono	
Transmission length	: 300m	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2011	
Ownership	: Single owner	
End-use HHs	:1	
End-use others	: 1	English centre.
NOTES		
He says he changes from the 3kW to a 5kW generator in wet season. For 5 meters head, we would need 100 l/s to produce 2.5kW.		
He provides energy for an English centre.		
He gained the knowledge of how to do it by talking to the other neighbouring projects.		

Figure B53. CA.6 Natural pond with intake.

Figure B54. CA.6 Artificial pond for fish farming and penstock crossing above it (right hand).

Table B30. Synopsis of CA.7 scheme.

Synopsis of Upper Tatei Leu Micro Hydro Project		
Site file: CA7 – Upper Tatei Leu		**Location** Upper Tatai Leu, Thmor Bang, Koh Kong
Visit date: 15th of June 2016		**GPS:** 11.7952, 103.4964
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:2.5m **Head$_n$**	:	
Design flow	: 200 lps	Unknown number, estimated from pictures
Designed power output	: 3kW	
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 0 m	
Length penstock	: 5 m	2x12 inch PVC?
Turbine	:Kaplan	
Generator	:10kW mono	Estimated
Transmission length	: 700m	
Project total cost	: 2,000 USD	
Cost/kW	: 670 USD	
Electrified date	: 2014	
Ownership	: Single owner	
End-use HHs	:12	
End-use others	: 0	
NOTES		
Machinery produced in Cambodia.		

Figure B55. CA.7 Weir, dual penstock and electromechanical group.

Figure B56. CA.7 Generator, corrector belt and turbine.

Synopsis of the schemes visited in the Philippines

Table B31. Synopsis of PH.1 scheme.

Synopsis of Lapat Micro Hydro Project		
Site file: PH1 - Lapat		**Location** Lapat, conner, Apayao, Luzon
Visit date: 28th of June 2016		**GPS:** 17.7622, 121.2743
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$:80m **Head$_n$**	: ---	
Design flow	: 25 lps	Estimation
Designed power output	: 15kW	From generator
Actual power output	: ---	
Overall efficiency	: ---	
Length headrace	: 1.2 km	Earth channel
Length penstock	: 160 m	Polyethylene
Turbine	: Propeller	
Generator	:18.4 KVA mono	
Transmission length	: 1km	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2009	
Ownership	: Community	
End-use HHs	: 58	28+16+14 (three different sitios)
End-use others	: 0	
NOTES		
On between 5pm to 8am. 1 HH pays PHP 50/ month. They have suffered landslides during typhoon season twice. In wet season the forebay over floods easily.		
Penstock is in really bad condition. SIBAT argues burying the penstock prevents damage by fire and landslides.		
Although national grid is around, they don’t want to connect due to its high price (PHP 8/kWh) and unreliability.		

Figure B57. PH.1 Headrace canal and forebay tank.

Figure B58. PH.1 Resistors for the ELC system.

Table B32. Synopsis of PH.2 scheme.

Synopsis of Bubog Micro Hydro Project		
Site file: PH2 - Bubog		**Location** Bubog, Conner, Apayao, Luzon
Visit date: 29th of June 2016		**GPS:** 17.7345, 121.2348
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: Head$_n$	: 43.5	
Design flow	: 20 lps	Estimation
Designed power output	: 5kW	From generator
Actual power output	: 5kW	
Overall efficiency	: ---	
Length headrace	: ---	Earth channel
Length penstock	: 96 m	Polyethylene
Turbine	: Crossflow	
Generator	:6.4 KVA mono	
Transmission length	: 50km	
Project total cost	:	
Cost/kW	:	
Electrified date	: 2007	
Ownership	: Community	
End-use HHs	: 14	
End-use others	: 1	Rice mill
NOTES		
The intake, made of wood, gets damaged often, and repaired fast.		

Figure B59. PH.2 Powerhouse with electromechanical group.

Figure B60. PH.2 Rice huller mechanically powered.

Table B33. Synopsis of PH.3 scheme.

Synopsis of Buneg Micro Hydro Project			
Site file:	PH3 - Buneg	**Location**	Buneg, Conner, Apayao, Luzon
Visit date:	30th of June 2016	**GPS:**	17.7253, 121.1846
PARAMATER	**VALUE**	**COMMENTS**	
Head$_g$: 52	**Head$_n$** :		
Design flow	: 20 lps	From report	
Designed power output	: 7kW		
Actual power output	: 6kW		
Overall efficiency	: ---		
Length headrace	: 384	Earth channel	
Length penstock	: 105 m	6 inch (18x6) Polyethylene	
Turbine	: Crossflow		
Generator	:10 KW mono		
Transmission length	: 50m	(total line 440m)	
Project total cost	: 12354		
Cost/kW	: 1764		
Electrified date	: 2002		
Ownership	: Community		
End-use HHs	: 43		
End-use others	: 2	Rice mill (1.5kw), Sugar cane mill (1.4kW)	
NOTES			
Works from 5pm to 7am. PHP 20/month			
The scheme managed to accumulate PHP 100.000, which has been used for loans to the community.			
They started with an operator rotation system, with yearly change. Now they have only two (Anselmo and Benigno).			
Owner of land gets some money.			

Figure B61. PH.3 Detail of interior of crossflow turbine.

Figure B62. PH.3 Sugar cane press electrically powered.

Table B34. Synopsis of PH.4 scheme.

Synopsis of Katablangan Micro Hydro Project		
Site file: PH4- Katablangan		**Location** Katablangan, Conner, Apayao, Luzon
Visit date: 2nd of July 2016		**GPS:** 17.7961, 121.1562
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 10 **Head$_n$**	: 9	
Design flow	: 120 lps	From report
Designed power output	: 7kW	
Actual power output	: 7kW	
Overall efficiency	: ---	
Length headrace	: 1km	Earth channel + Concrete section
Length penstock	: 40 m	12 inch HDPE
Turbine	: Crossflow	
Generator	:15 KW mono	
Transmission length	: 200m	(total line 440m)
Project total cost	:	
Cost/kW	:	
Electrified date	: 2000	
Ownership	: Community	
End-use HHs	: 52	
End-use others	: 1	Carpentry
NOTES		
Land of powerhouse between two properties. Got donated.		
1 operator making PHP400/month. They used to have two.		
Operates between 4-9pm and 4-6am.		

Figure B63. PH.4 Semi-destroyed intake structure.

Figure B64. PH.4 Maintenance procedures on turbine and bearings (checking for vibrations).

Table B35. Synopsis of PH.5 scheme.

Synopsis of Baclao Micro Hydro Project			
Site file:	PH 5 - Baclao	**Location**	Baclao, Cauayan, Negros Occidental, Visayas
Visit date:	9th of July 2016	**GPS:**	9.8386, 122.4558
PARAMATER	**VALUE**	**COMMENTS**	
Head$_g$: 105 **Head$_n$** :			
Design flow	: 55 lps	From VertCapTech	
Designed power output	: 34kW		
Actual power output	: 0kW	System not functioning	
Overall efficiency	: ---		
Length headrace	: 700	300 m Corrugated HD polyethylene pipe 14’’	
Length penstock	: 300m	10 inch GI	
Turbine	: Pelton, 2 jet		
Generator	:42 KVA tri	Same as PH7 and PH8	
Transmission length	: 3km		
Project total cost	: 132.000USD	PHP6.2m	
Cost/kW	: 4125 USD		
Electrified date	: 2009	Lasted until 2015	
Ownership	: Community		
End-use HHs	: 100		
End-use others	: 1	Rice mills	
NOTES			
Over dimensioned scheme. Probably to cover for the budget that required spending.			
Penstock unnecessary wide, which broke completely.			
Community left without contact from funders or Iamog.			
Pelton turbine broke fast, no one helped them repair it. Perfect example of “medal scheme”.			

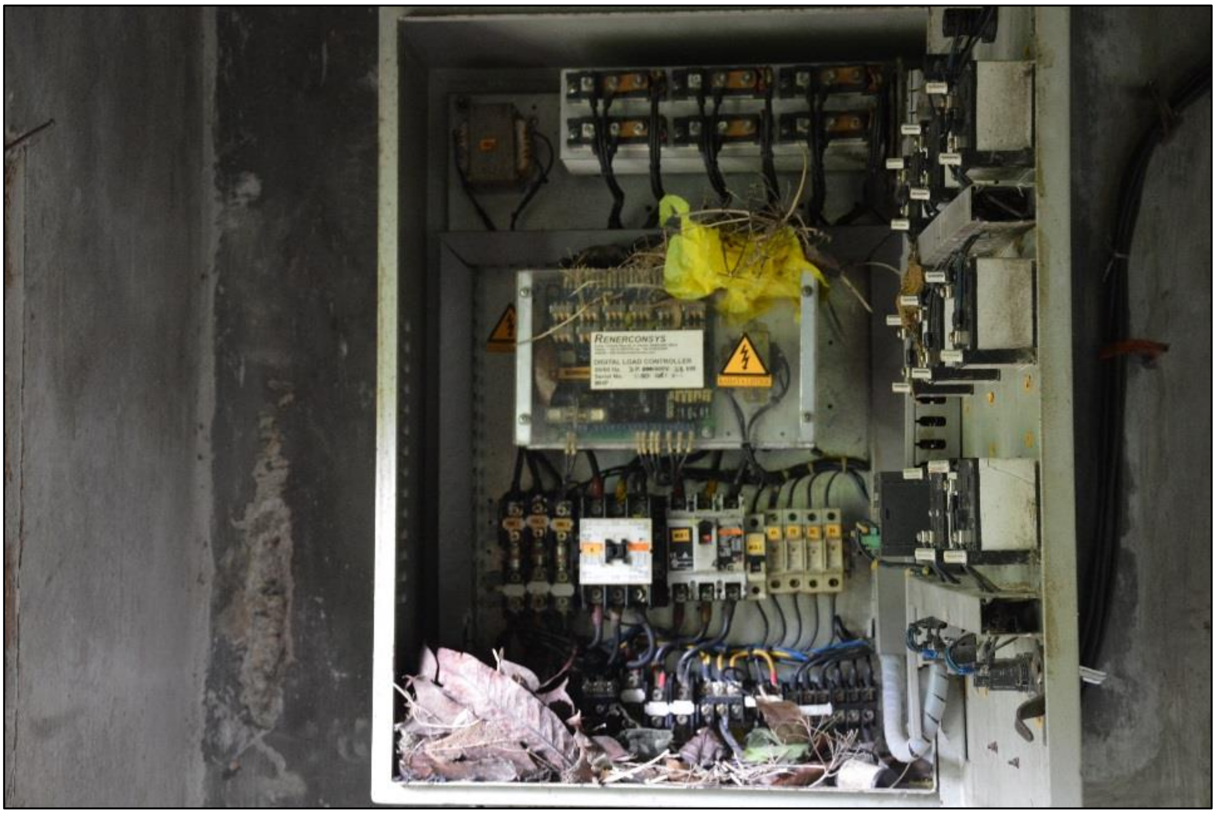


Figure B65. PH.5 Interior of ELC electric panel.

Figure B66. PH.5 Transformer next to powerhouse.

Table B36. Synopsis of PH.6 scheme.

Synopsis of Tikoy Tikoy Micro Hydro Project		
Site file: PH6 - Tikoy Tikoy		**Location** Tikoy Tikoy, La Castellana, Negros Occidental, Visayas
Visit date: 10th of July 2016		**GPS:** 10.3066, 123.1331
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 1.5 **Head$_n$**	:	
Design flow	: 500 lps	Estimated value
Designed power output	:5kW	
Actual power output	: 0kW	System not functioning
Overall efficiency	: ---	
Length headrace	: 100m	Concrete canal
Length penstock	: 0	No penstock
Turbine	: Mill	
Generator	:10 KVA mono	Estimated value
Transmission length	: 0m	Central to the community.
Project total cost	:	
Cost/kW	:	
Electrified date	: 2005	Lasted until 2010
Ownership	: Mayor	
End-use HHs	: 30	
End-use others	: 2	Rice and corn mills
NOTES		
From 2005 to 2010 30 HH where connected to the MHP. People started to swap to the national grid, for it provided more electricity (households where limited to 2 light bulbs .)		
The community wanted more electricity, refrigerators, etc, so the swapped. When enough people swapped so the funds could not cover the maintenance and operator fees, they stopped it, 2010.		
PHP1/bulb*day. Most people had 2, PHP60 /month.		
Functioning from 6pm to 6 am.		

Figure B67. PH.6 Headrace canal travelling next to river.

Figure B68. PH.6 Rudimentary wheel, generator and belts for other mechanically powered machinery.

Table B37. Synopsis of PH.7 scheme.

Synopsis of Vergara Micro Hydro Project		
Site file: PH 7 - Vergara		**Location** Vergara, Toboso, Negros Occidental, Visayas
Visit date: 11th of July 2016		**GPS:** 10.7205, 123.3528
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 18 **Head$_n$**	: 17.4	Estimated value
Design flow	: 275 lps	From calculations
Designed power output	: 28kW	
Actual power output	: 28kW	
Overall efficiency	: ---	
Length headrace	:70	Concrete
Length penstock	: 180m	220 , 580mm rolled welded pipe
Turbine	: Crossflow	
Generator	:42 KVA tri	Same as PH5 and PH8
Transmission length	: 1km	In between the two sitios
Project total cost	: 157.000USD	PHP7.4m
Cost/kW	: 4900 USD	
Electrified date	: 2008	
Ownership	: Community	
End-use HHs	: 200	Sitio Vergara and sitio Mactuoc
End-use others	: 0	Too scared of outages.
NOTES		
It provides power to two sitios, with the powerhouse located in between.		
They have lost contact with Iamog and funders.		
Rich community that had no problem to pay an average of PHP500/month. Rate of 6.5 kWh plus flat rate of P85.		
Another “medal scheme”, over dimensioned, but this one has lasted.		

Figure B69. PH.7 Weir and intake structure.

Figure B70. PH.7 Forebay tank and penstock.

Table B38. Synopsis of PH.8 scheme.

Synopsis of Balea Micro Hydro Project		
Site file: PH8 - Balea		**Location** Balea, Calatrava, Negros Occidental, Visayas
Visit date: 12th of July 2016		**GPS:** 10.6384, 123.3534
PARAMATER	**VALUE**	**COMMENTS**
Head$_g$: 79 **Head$_n$**	: 73.39	From pressure gauge
Design flow	: 50 lps	From calculations
Designed power output	: 22kW	
Actual power output	: 22kW	
Overall efficiency	: ---	
Length headrace	:500	Buried reticulated pipe
Length penstock	: 150m	12 inch GI
Turbine	: Crossflow	
Generator	:42 KVA tri	Same as PH5 and PH7
Transmission length	: 5km	No transformer!
Project total cost	: 161.000USD	PHP7.6m
Cost/kW	: 5000 USD	
Electrified date	: 2008	Lasted until 2015
Ownership	: Community	
End-use HHs	: 150	Sitio Vergara and sitio Mactuoc
End-use others	: 0	Prohibited, for lack of electricity.
NOTES		
Meetings held every other month. They have lost contact with Iamog and funders.		
Another rich community that had no problem to pay an average of PHP500/month. Rate of 6.5 kWh plus flat rate of P115.		
Another “medal scheme”, over dimensioned, but this one has lasted.		
No transformer has become a big problem. 5km is too far.		

Figure B71. PH.8 Powerhouse interior with electromechanical group.

Figure B72. PH.8 Caged resistors from the ELC group.

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ANNEX C – MHP-PAT Code

The following is the code in C++ required for the validation of the MHP-PAT.

```
#include <armadillo>
#include <ctime>
#include <iostream>
using namespace arma;
// 1- DEFINITION OF ALL PAIR-WISE COMPARISON, MATRICES AND EIGENVECTORS
// 1.1- FUNCTION TO GENERATE ALL COMBINATIONS
void generateVectorPool()
{
   mat START_POINTS;

   // TRY TO READ FROM DISK THE MATRIX OF START_POINTS, WHICH CONTAINS ALL THE POSSIBLE PAIR-WISE COMPARISON VALUES. IF IT DOESN'T FIND IT, IT CREATES IT.
   if(START_POINTS.load("STARTPOINTS", raw_ascii, false) == false) {
      // IF FILE DOES NOT EXIST
      // CREATE DEFAULT START POINTS
      START_POINTS.zeros(14, 7);

      START_POINTS(0, 0) = 1. / 5.;
      START_POINTS(0, 1) = 1. / 3.;
      START_POINTS(0, 2) = 1.;
      START_POINTS(0, 3) = 3.;
      START_POINTS(0, 4) = 5.;

      START_POINTS(1, 0) = 3.;
      START_POINTS(1, 1) = 5.;
      START_POINTS(1, 2) = 7.;

      START_POINTS(2, 0) = 1. / 5.;
      START_POINTS(2, 1) = 1. / 3.;
      START_POINTS(2, 2) = 1.;
      START_POINTS(2, 3) = 3.;
```

```
START_POINTS(2, 4) = 5.;

START_POINTS(3, 0) = 1. / 5.;
START_POINTS(3, 1) = 1. / 3.;
START_POINTS(3, 2) = 1.;
START_POINTS(3, 3) = 3.;
START_POINTS(3, 4) = 5.;

START_POINTS(4, 0) = 1. / 5.;
START_POINTS(4, 1) = 1. / 3.;
START_POINTS(4, 2) = 1.;
START_POINTS(4, 3) = 3.;
START_POINTS(4, 4) = 5.;

START_POINTS(5, 0) = 1. / 3.;
START_POINTS(5, 1) = 1.;
START_POINTS(5, 2) = 3.;
START_POINTS(5, 3) = 5.;
START_POINTS(5, 4) = 7.;

START_POINTS(6, 0) = 1. / 3.;
START_POINTS(6, 1) = 1.;
START_POINTS(6, 2) = 3.;
START_POINTS(6, 3) = 5.;
START_POINTS(6, 4) = 7.;

START_POINTS(7, 0) = 1. / 3.;
START_POINTS(7, 1) = 1.;
START_POINTS(7, 2) = 3.;
START_POINTS(7, 3) = 5.;
START_POINTS(7, 4) = 7.;

START_POINTS(8, 0) = 1.;
START_POINTS(8, 1) = 3.;
```

```
    START_POINTS(8, 2) = 5.;
    START_POINTS(8, 3) = 7.;

    START_POINTS(9, 0) = 1.;
    START_POINTS(9, 1) = 3.;
    START_POINTS(9, 2) = 5.;
    START_POINTS(9, 3) = 7.;

    START_POINTS(10, 0) = 1. / 3.;
    START_POINTS(10, 1) = 1.;
    START_POINTS(10, 2) = 3.;
    START_POINTS(10, 3) = 5.;
    START_POINTS(10, 4) = 7.;

    START_POINTS(11, 0) = 1. / 3.;
    START_POINTS(11, 1) = 1.;
    START_POINTS(11, 2) = 3.;
    START_POINTS(11, 3) = 5.;
    START_POINTS(11, 4) = 7.;

    START_POINTS(12, 0) = 1.;
    START_POINTS(12, 1) = 3.;
    START_POINTS(12, 2) = 5.;
    START_POINTS(12, 3) = 7.;

    START_POINTS(13, 0) = 1.;
    START_POINTS(13, 1) = 3.;
    START_POINTS(13, 2) = 5.;
    START_POINTS(13, 3) = 7.;

    // SAVE AS PLAIN TEXT FOR REUSE
    START_POINTS.save("STARTPOINTS", raw_ascii);
};
```

```
// COLLECT THE NUMBER OF NONZERO ELEMENTS FOR EACH LINE, SO THAT WE KNOW HOW MANY TIMES WE HAVE TO LOOP

uvec SUM = sum(START_POINTS > 0, 1);

    // 1.2- FOR EACH POSSIBILITY WE CREATE EACH ONE OF THE MATRICES OF LEVELS 2 AND 3 AND THEIR EIGENVECTORS

mat TMP_MAT;

vec TMP_EIG;

int IDX;


//DEFINE ALL LEVEL 2 MATRICES, THEIR EIGENVECTORS, AND THE PAIR-WISE COMPARISON (LEVEL2_REF)

mat LEVEL2_EIG, LEVEL2_REF, LEVEL2_44(4, 4);

LEVEL2_44.eye(); // DIAGONAL ELEMENTS ARE ALWAYS 1


// TRY TO LOAD EXISTING FILES LEVEL2_EIG AND LEVEL2_REF FIRST

if(LEVEL2_EIG.load("LEVEL2_EIG", auto_detect, false) == false ||

  LEVEL2_REF.load("LEVEL2_REF", auto_detect, false) == false) {

  // IF FILES DON'T EXIST THEN CREATE EMPTY MATRICES TO STORE EIGENVECTORS

  LEVEL2_EIG.zeros(4, SUM(0) * SUM(1) * SUM(2));

  // STORES CORRESPONDING ENTRIES FOR EACH COMBINATION

  LEVEL2_REF.zeros(3, SUM(0) * SUM(1) * SUM(2));

  IDX = 0;

  // FILL CELLS OF LEVEL 2 MATRIX

  for(int i = 0; i < 7; i++) {

    if(START_POINTS(0, i) != 0) {

      LEVEL2_44(0, 1) = START_POINTS(0, i);

      LEVEL2_44(1, 0) = 1. / LEVEL2_44(0, 1);

      for(int j = 0; j < 7; j++) {

        if(START_POINTS(1, j) != 0) {

          LEVEL2_44(0, 2) = START_POINTS(1, j);

          LEVEL2_44(2, 0) = 1. / LEVEL2_44(0, 2);

          LEVEL2_44(1, 2) = LEVEL2_44(0, 2) / LEVEL2_44(0, 1);

          LEVEL2_44(2, 1) = 1. / LEVEL2_44(1, 2);

          for(int k = 0; k < 7; k++) {

            if(START_POINTS(2, k) != 0) {
```

```
                        LEVEL2_44(0, 3) = START_POINTS(2, k);
                        LEVEL2_44(3, 0) = 1. / LEVEL2_44(0, 3);
                        LEVEL2_44(1, 3) = LEVEL2_44(0, 3) / LEVEL2_44(0, 1);
                        LEVEL2_44(3, 1) = 1. / LEVEL2_44(1, 3);
                        LEVEL2_44(2, 3) = LEVEL2_44(0, 3) / LEVEL2_44(0, 2);
                        LEVEL2_44(3, 2) = 1. / LEVEL2_44(2, 3);
                        TMP_MAT = LEVEL2_44 * LEVEL2_44 * LEVEL2_44 * LEVEL2_44; //
POWER METHOD
                        LEVEL2_EIG.col(IDX) =
                          TMP_MAT.col(0) / sum(TMP_MAT.col(0)); // CALCULATING
EIGENVECTORS AND STORING THEIR INDEXES FOR _REF MATRICES
                        LEVEL2_REF(0, IDX) = START_POINTS(0, i);
                        LEVEL2_REF(1, IDX) = START_POINTS(1, j);
                        LEVEL2_REF(2, IDX) = START_POINTS(2, k);
                        IDX = IDX + 1;
                      }
                    }
                  }
                }
              }
            }
            // SAVE FOR FILES TO USE THEM LATER
            LEVEL2_EIG.save("LEVEL2_EIG");
            LEVEL2_REF.save("LEVEL2_REF");
        };
              // SAME AS PREVIOUSLY, NOW FOR LEVEL 3
        mat LEVEL31_EIG, LEVEL31_REF, LEVEL31_66(6, 6);
        LEVEL31_66.eye();

        if(LEVEL31_EIG.load("LEVEL31_EIG", auto_detect, false) == false ||
            LEVEL31_REF.load("LEVEL31_REF", auto_detect, false) == false) {
            LEVEL31_EIG.zeros(6, SUM(3) * SUM(4) * SUM(5) * SUM(6) * SUM(7));
            LEVEL31_REF.zeros(5, SUM(3) * SUM(4) * SUM(5) * SUM(6) * SUM(7));
            IDX = 0;
            for(int i = 0; i < 7; i++) {
```

```
if(START_POINTS(3, i) != 0) {
    LEVEL31_66(0, 1) = START_POINTS(3, i);
    LEVEL31_66(1, 0) = 1. / LEVEL31_66(0, 1);
    for(int j = 0; j < 7; j++) {
        if(START_POINTS(4, j) != 0) {
            LEVEL31_66(0, 2) = START_POINTS(4, j);
            LEVEL31_66(2, 0) = 1. / LEVEL31_66(0, 2);
            LEVEL31_66(1, 2) = LEVEL31_66(0, 2) / LEVEL31_66(0, 1);
            LEVEL31_66(2, 1) = 1. / LEVEL31_66(1, 2);
            for(int k = 0; k < 7; k++) {
                if(START_POINTS(5, k) != 0) {
                    LEVEL31_66(0, 3) = START_POINTS(5, k);
                    LEVEL31_66(3, 0) = 1. / LEVEL31_66(0, 3);
                    for(int ii = 1; ii < 3; ii++) {
                        LEVEL31_66(ii, 3) =
                            LEVEL31_66(0, 3) / LEVEL31_66(0, ii);
                        LEVEL31_66(3, ii) = 1. / LEVEL31_66(ii, 3);
                    };
                    for(int l = 0; l < 7; l++) {
                        if(START_POINTS(6, l) != 0) {
                            LEVEL31_66(0, 4) = START_POINTS(6, l);
                            LEVEL31_66(4, 0) = 1. / LEVEL31_66(0, 4);
                            for(int ii = 1; ii < 4; ii++) {
                                LEVEL31_66(ii, 4) =
                                    LEVEL31_66(0, 4) / LEVEL31_66(0, ii);
                                LEVEL31_66(4, ii) = 1. / LEVEL31_66(ii, 4);
                            };
                            for(int m = 0; m < 7; m++) {
                                if(START_POINTS(7, m) != 0) {
                                    LEVEL31_66(0, 5) = START_POINTS(7, m);
                                    LEVEL31_66(5, 0) = 1. / LEVEL31_66(0, 5);
                                    for(int ii = 1; ii < 5; ii++) {
                                        LEVEL31_66(ii, 5) = LEVEL31_66(0, 5) /
                                            LEVEL31_66(0, ii);
```

```
                        LEVEL31_66(5, ii) =
                           1. / LEVEL31_66(ii, 5);
                     };
                     TMP_MAT = LEVEL31_66 * LEVEL31_66 *
                        LEVEL31_66 * LEVEL31_66;
                     LEVEL31_EIG.col(IDX) =
                        TMP_MAT.col(0) / sum(TMP_MAT.col(0));
                     LEVEL31_REF(0, IDX) = START_POINTS(3, i);
                     LEVEL31_REF(1, IDX) = START_POINTS(4, j);
                     LEVEL31_REF(2, IDX) = START_POINTS(5, k);
                     LEVEL31_REF(3, IDX) = START_POINTS(6, l);
                     LEVEL31_REF(4, IDX) = START_POINTS(7, m);
                     IDX = IDX + 1;
                  }
               }
            }
         }
      }
   }
  }
 }
}
   }
   LEVEL31_EIG.save("LEVEL31_EIG");
   LEVEL31_REF.save("LEVEL31_REF");
};

mat LEVEL32_EIG, LEVEL32_REF, LEVEL32_44(4, 4);
LEVEL32_44.eye();

if(LEVEL32_EIG.load("LEVEL32_EIG", auto_detect, false) == false ||
   LEVEL32_REF.load("LEVEL32_REF", auto_detect, false) == false) {
   LEVEL32_EIG.zeros(4, SUM(8) * SUM(9) * SUM(10));
   LEVEL32_REF.zeros(3, SUM(8) * SUM(9) * SUM(10));
```

```
IDX = 0;
for(int i = 0; i < 7; i++) {
    if(START_POINTS(8, i) != 0) {
        LEVEL32_44(0, 1) = START_POINTS(8, i);
        LEVEL32_44(1, 0) = 1. / LEVEL32_44(0, 1);
        for(int j = 0; j < 7; j++) {
            if(START_POINTS(9, j) != 0) {
                LEVEL32_44(0, 2) = START_POINTS(9, j);
                LEVEL32_44(2, 0) = 1. / LEVEL32_44(0, 2);
                LEVEL32_44(1, 2) = LEVEL32_44(0, 2) / LEVEL32_44(0, 1);
                LEVEL32_44(2, 1) = 1. / LEVEL32_44(1, 2);
                for(int k = 0; k < 7; k++) {
                    if(START_POINTS(10, k) != 0) {
                        LEVEL32_44(0, 3) = START_POINTS(10, k);
                        LEVEL32_44(3, 0) = 1. / LEVEL32_44(0, 3);
                        LEVEL32_44(1, 3) = LEVEL32_44(0, 3) / LEVEL32_44(0, 1);
                        LEVEL32_44(3, 1) = 1. / LEVEL32_44(1, 3);
                        LEVEL32_44(2, 3) = LEVEL32_44(0, 3) / LEVEL32_44(0, 2);
                        LEVEL32_44(3, 2) = 1. / LEVEL32_44(2, 3);
                        TMP_MAT =
                            LEVEL32_44 * LEVEL32_44 * LEVEL32_44 * LEVEL32_44;
                        LEVEL32_EIG.col(IDX) =
                            TMP_MAT.col(0) / sum(TMP_MAT.col(0));
                        LEVEL32_REF(0, IDX) = START_POINTS(8, i);
                        LEVEL32_REF(1, IDX) = START_POINTS(9, j);
                        LEVEL32_REF(2, IDX) = START_POINTS(10, k);
                        IDX = IDX + 1;
                    }
                }
            }
        }
    }
}
LEVEL32_EIG.save("LEVEL32_EIG");
```

```
    LEVEL32_REF.save("LEVEL32_REF");
};

mat LEVEL33_EIG, LEVEL33_REF, LEVEL33_22(2, 2);
LEVEL33_22.eye();

if(LEVEL33_EIG.load("LEVEL33_EIG", auto_detect, false) == false ||
    LEVEL33_REF.load("LEVEL33_REF", auto_detect, false) == false) {
    LEVEL33_EIG.zeros(2, SUM(11));
    LEVEL33_REF.zeros(1, SUM(11));
    IDX = 0;
    for(int i = 0; i < 7; i++) {
        if(START_POINTS(11, i) != 0) {
            LEVEL33_22(0, 1) = START_POINTS(11, i);
            LEVEL33_22(1, 0) = 1. / LEVEL33_22(0, 1);
            TMP_MAT = LEVEL33_22 * LEVEL33_22 * LEVEL33_22 * LEVEL33_22;
            LEVEL33_EIG.col(IDX) = TMP_MAT.col(0) / sum(TMP_MAT.col(0));
            LEVEL33_REF(0, IDX) = START_POINTS(11, i);
            IDX = IDX + 1;
        }
    }
    LEVEL33_EIG.save("LEVEL33_EIG");
    LEVEL33_REF.save("LEVEL33_REF");
};

mat LEVEL34_EIG, LEVEL34_REF, LEVEL34_33(3, 3);
LEVEL34_33.eye();

if(LEVEL34_EIG.load("LEVEL34_EIG", auto_detect, false) == false ||
    LEVEL34_REF.load("LEVEL34_REF", auto_detect, false) == false) {
    LEVEL34_EIG.zeros(3, SUM(12) * SUM(13));
    LEVEL34_REF.zeros(2, SUM(12) * SUM(13));
    IDX = 0;
    for(int i = 0; i < 7; i++) {
```

```
        if(START_POINTS(12, i) != 0) {
          LEVEL34_33(0, 1) = START_POINTS(12, i);
          LEVEL34_33(1, 0) = 1. / LEVEL34_33(0, 1);
          for(int j = 0; j < 7; j++) {
            if(START_POINTS(13, j) != 0) {
              LEVEL34_33(0, 2) = START_POINTS(13, j);
              LEVEL34_33(2, 0) = 1. / LEVEL34_33(0, 2);
              LEVEL34_33(1, 2) = LEVEL34_33(0, 2) / LEVEL34_33(0, 1);
              LEVEL34_33(2, 1) = 1. / LEVEL34_33(1, 2);
              TMP_MAT = LEVEL34_33 * LEVEL34_33 * LEVEL34_33 * LEVEL34_33;
              LEVEL34_EIG.col(IDX) = TMP_MAT.col(0) / sum(TMP_MAT.col(0));
              LEVEL34_REF(0, IDX) = START_POINTS(12, i);
              LEVEL34_REF(1, IDX) = START_POINTS(13, j);
              IDX = IDX + 1;
            }
          }
        }
      }
      LEVEL34_EIG.save("LEVEL34_EIG");
      LEVEL34_REF.save("LEVEL34_REF");
    };

    // DEFINITION OF LEVEL 4 MATRICES (WITH FIXED VALUES)
    // COMPUTE AND STORE CORRESPONDING ENGENVECTOR FOR REUSE
    vec REF33;
    if(REF33.load("REF33", auto_detect, false) == false) {
      mat REF33MAT(3, 3);
      REF33MAT.eye();
      REF33MAT(0, 1) = 3.;
      REF33MAT(0, 2) = 5.;
      REF33MAT(1, 2) = REF33MAT(0, 2) / REF33MAT(0, 1);
      REF33MAT(1, 0) = 1. / REF33MAT(0, 1);
      REF33MAT(2, 0) = 1. / REF33MAT(0, 2);
      REF33MAT(2, 1) = 1. / REF33MAT(1, 2);
```

```
        TMP_MAT = REF33MAT * REF33MAT * REF33MAT * REF33MAT;
        REF33 = TMP_MAT.col(0) / sum(TMP_MAT.col(0));
        REF33.save("REF33");
    };

    vec REF44;
    if(REF44.load("REF44", auto_detect, false) == false) {
        mat REF44MAT(4, 4);
        REF44MAT.eye();
        REF44MAT(0, 1) = 3.;
        REF44MAT(0, 2) = 5.;
        REF44MAT(0, 3) = 7.;
        REF44MAT(1, 2) = REF44MAT(0, 2) / REF44MAT(0, 1);
        REF44MAT(1, 3) = REF44MAT(0, 3) / REF44MAT(0, 1);
        REF44MAT(2, 3) = REF44MAT(0, 3) / REF44MAT(0, 2);

        REF44MAT(1, 0) = 1. / REF44MAT(0, 1);
        REF44MAT(2, 0) = 1. / REF44MAT(0, 2);
        REF44MAT(3, 0) = 1. / REF44MAT(0, 3);
        REF44MAT(2, 1) = 1. / REF44MAT(1, 2);
        REF44MAT(3, 1) = 1. / REF44MAT(1, 3);
        REF44MAT(3, 2) = 1. / REF44MAT(2, 3);
        TMP_MAT = REF44MAT * REF44MAT * REF44MAT * REF44MAT;
        REF44 = TMP_MAT.col(0) / sum(TMP_MAT.col(0));
        REF44.save("REF44");
    };
};
            // 2- GET RESULTS FOR EACH SCHEME FOR EACH COMBINATION OF PAIR-WISE COMPARISON BY LOOPING
int main()
{
    // 2.1- LOAD ALL VARIABLES AND MATRICES
    mat LEVEL2_EIG, LEVEL2_REF, LEVEL31_EIG, LEVEL31_REF, LEVEL32_EIG, LEVEL32_REF,
```

```
    LEVEL33_EIG, LEVEL33_REF, LEVEL34_EIG, LEVEL34_REF, REF33, REF44, FACTOR31,
    FACTOR32, FACTOR33, FACTOR34;


  vec AW31(24), AW32(13), AW33(6), AW34(9), TMP31, TMP32, TMP33, TMP34, TMPA, TMPB,
    TMPC, TMPD, TMPE, AHP, SF, MAX_AHP, MAX_AW31, MAX_AW32, MAX_AW33, MAX_AW34;


  // CALL FUNCTION TO GENERATE ALL NECESSARY DATA, SECTION 1
  generateVectorPool();


  // LOAD FILES GENERATED IN LAST FUNCTION
  LEVEL2_EIG.load("LEVEL2_EIG");
  LEVEL2_REF.load("LEVEL2_REF");
  LEVEL31_EIG.load("LEVEL31_EIG");
  LEVEL31_REF.load("LEVEL31_REF");
  LEVEL32_EIG.load("LEVEL32_EIG");
  LEVEL32_REF.load("LEVEL32_REF");
  LEVEL33_EIG.load("LEVEL33_EIG");
  LEVEL33_REF.load("LEVEL33_REF");
  LEVEL34_EIG.load("LEVEL34_EIG");
  LEVEL34_REF.load("LEVEL34_REF");
  REF33.load("REF33");
  REF44.load("REF44");


  // CHECK IF THE LEVEL 4 CHOICE MATRIX EXISTS (35 SCHEMES BY 52 (7X4 + 8X3))
  int INFO = 0;
  INFO += FACTOR31.load("FACTOR31", auto_detect, false);
  INFO += FACTOR32.load("FACTOR32", auto_detect, false);
  INFO += FACTOR33.load("FACTOR33", auto_detect, false);
  INFO += FACTOR34.load("FACTOR34", auto_detect, false);


  INFO += SF.load("SUCCESSFRAME", auto_detect, false);
```

```
// IF IT FAILS TO LOAD THE FILES THEN EXIT
if(INFO != 5) {
    printf("Need FACTOR31, FACTOR32, FACTOR33, FACTOR34, SUCCESSFRAME.\n");
    return 0;
}


// 2.2- SPLIT PROCESS INTO SEVERAL SUBPROCESSES ACCORDING TO THE NUMBER OF POSSIBILITIES OF LEVEL 3.3 MATRIX
unsigned int SUBSET = 0;
std::cout << "Choose one subset to solve: (0-" << LEVEL33_REF.n_cols - 1 // PRINTING INFORMATION ON THE SCREEN
        << ", 8 to quit)\n";
std::cin >> SUBSET;  // READ SUBSET CHOSEN (0-6)
if(SUBSET == 8 || SUBSET > LEVEL33_REF.n_cols || SUBSET < 0) return 0; // CHECK THAT THE POSSIBILITIES ARE EQUAL OR SMALLER THAN THE SIZE OF 3.3


int S_TIME = clock();


// STORES MAXIMUM CORRELATION
double MAX = 0, CORRELATION = 0;
// STORES THE ENTRY INDIXES (THE LOOP ORDER) OF MAXIMUM CORRELATION FOUND (LATER WE USE THESE INDEXES TO GET ENTRY ELEMENTS FOR ANY OF THE _REF MATRICES)
uvec IDX(5);
for(unsigned int i = 0; i < LEVEL2_EIG.n_cols; i++) {
    printf("Completed: %.2f%%.\n", 100. * (i + 1.) / double(LEVEL2_EIG.n_cols)); // CALCULATION IN % OF HOW MANY LOOPS OF THE AUTERLOOP HAVE BEEN DONE
    // TEMP VARIABLES OF THE AGGREGATED WEIGHTS OF LEVEL2XLEVEL4
    TMPA = LEVEL2_EIG(0, i) * REF44;
    TMPB = LEVEL2_EIG(1, i) * REF44;
    TMPC = LEVEL2_EIG(1, i) * REF33;
    TMPD = LEVEL2_EIG(2, i) * REF33;
    TMPE = LEVEL2_EIG(3, i) * REF33;
    for(unsigned int j = 0; j < LEVEL31_EIG.n_cols; j++) {
        // ELEMENT-WISE ASSIGNMENT FASTER THAN KRONECKER PRODUCT. MULTIPLY NOW BY LEVEL 3 TO HAVE FINAL AGGREGATED WEIGHT
```

```
TMP31 = FACTOR31 * kron(LEVEL31_EIG.col(j), TMPA); //LEVEL2 X LEVEL4 X LEVEL3.1
for(unsigned int k = 0; k < LEVEL32_EIG.n_cols; k++) {
    AW32(0) = LEVEL32_EIG(0, k) * TMPB(0); ////LEVEL2 X LEVEL4 X LEVEL3.2
    AW32(1) = LEVEL32_EIG(0, k) * TMPB(1);
    AW32(2) = LEVEL32_EIG(0, k) * TMPB(2);
    AW32(3) = LEVEL32_EIG(0, k) * TMPB(3);
    AW32(4) = LEVEL32_EIG(1, k) * TMPC(0);
    AW32(5) = LEVEL32_EIG(1, k) * TMPC(1);
    AW32(6) = LEVEL32_EIG(1, k) * TMPC(2);
    AW32(7) = LEVEL32_EIG(2, k) * TMPC(0);
    AW32(8) = LEVEL32_EIG(2, k) * TMPC(1);
    AW32(9) = LEVEL32_EIG(2, k) * TMPC(2);
    AW32(10) = LEVEL32_EIG(3, k) * TMPC(0);
    AW32(11) = LEVEL32_EIG(3, k) * TMPC(1);
    AW32(12) = LEVEL32_EIG(3, k) * TMPC(2);
    TMP32 = FACTOR32 * AW32;
    // for (unsigned int l = 0; l < LEVEL33_EIG.n_cols; l++) {
    for(unsigned int l = SUBSET; l < SUBSET + 1; l++) { //LEVEL2 X LEVEL4 X LEVEL3.3
        TMP33 = FACTOR33 * kron(LEVEL33_EIG.col(l), TMPD);
        for(unsigned int m = 0; m < LEVEL34_EIG.n_cols; m++) { // //LEVEL2 X LEVEL4 X LEVEL3.4
            TMP34 = FACTOR34 * kron(LEVEL34_EIG.col(m), TMPE);
            AHP = TMP31 + TMP32 + TMP33 + TMP34;  // SUM ALL SECTIONS TO GET FINAL SCORE FOR EACH OF THE 35 SCHEMES
            CORRELATION = as_scalar(cor(AHP, SF)); // CALCULATE CORRELATION
            // IF EXCEEDS CURRENT MAXIMUM REPLACE IT
            if(CORRELATION > MAX) {
                MAX_AW31 = AW31;
                MAX_AW32 = AW32;
                MAX_AW33 = AW33;
                MAX_AW34 = AW34;
                MAX_AHP = AHP;
                MAX = CORRELATION;
                IDX(0) = i;
```

```
                IDX(1) = j;
                IDX(2) = k;
                IDX(3) = l;
                IDX(4) = m;
            }
          }
        }
      }
    }
}
        // 2.3- PRINTING AHP RESULTS, PAIR-WISE COMPARISONS, AND TIME
int E_TIME = clock();

MAX_AW31.save("MAX_AW31", raw_ascii);
MAX_AW32.save("MAX_AW32", raw_ascii);
MAX_AW33.save("MAX_AW33", raw_ascii);
MAX_AW34.save("MAX_AW34", raw_ascii);
printf("Time: %.3f\n", (E_TIME - S_TIME) / double(CLOCKS_PER_SEC));
printf("The maximum correlation %.5f produced by combination: %lld, %lld, %lld, "
       "%lld, %lld.\n",
   MAX, IDX(0), IDX(1), IDX(2), IDX(3), IDX(4));
printf("The AHP vector is:\n");
MAX_AHP.print();
printf("The corresponding Level 2 matrix entries are:\n");
LEVEL2_REF.col(IDX(0)).print();
printf("The corresponding Level 31 matrix entries are:\n");
LEVEL31_REF.col(IDX(1)).print();
printf("The corresponding Level 32 matrix entries are:\n");
LEVEL32_REF.col(IDX(2)).print();
printf("The corresponding Level 33 matrix entries are:\n");
LEVEL33_REF.col(IDX(3)).print();
printf("The corresponding Level 34 matrix entries are:\n");
LEVEL34_REF.col(IDX(4)).print();
```

```
    printf("\n\nEnter any number to quit.\n");
    std::cin >> SUBSET;

    return 0;
};
```